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CORRECTIONS

MONTHLY WEATHER REVIEW, January 1951, vol. 79, No. 1, p. 18: In paragraph 1 under The Weather, the sentence beginning in line 10 should read as follows: "In addition, average cloudiness in those areas exceeded 60 percent (Chart VI–A) as well as the seasonal normal (Chart VI–B), sunshine was less than half of the maximum (Chart VII–A) and generally subnormal (Chart VII–B), and there was . . ."

Vol. 79, No. 1, p. 19: New title for Chart VI given in Notice of Change in Climatological Charts should read "Percentage of Sky Cover Between Sunrise and Sunset."

DEPARTMENT OF COMMERCE
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MONTHLY WEATHER REVIEW

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AN OBJECTIVE AID FOR FORECASTING SEPTEMBER THUNDERSTORMS AT DENVER, COLO.

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ABSTRACT

The climatology of September thunderstorms at Denver, Colo., is discussed. Data as near as possible to the time of occurrence of thunderstorms are studied to determine variables related to the occurrence of thunderstorms. The same variables from earlier data are investigated to determine their forecasting value. Three variables taken from the 2000 MST raobs and 700-mb. charts are ultimately used to obtain an objective aid for forecasting thunderstorms between midnight and midnight following the 2000 MST upper air chart. It is pointed out that for practical purposes this constitutes a forecast of afternoon and evening thunderstorms, or a forecast for 12–20 hours in advance. The conclusion is drawn that the objective aid developed should prove of value in forecasting September thunderstorms at Denver.

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INTRODUCTION

Most thunderstorms observed at Denver occur during the warmer months of June, July, and August when the maximum solar insolation occurs. For this reason most thunderstorm studies for the Denver area have been limited to these months. For example, H. V. Hightman [1] studied the relationship of mixing ratios to thunderstorm occurrence during 1941 and 1942; and Legg [2] using the same years investigated the position of the freezing level and the convective condensation level in connection with Denver thunderstorms. Epperly [3] used the summer months for the study of thunderstorm probability for the western portion of the United States.

Thunderstorms do occur at Denver in September, however, and, while the average number of thunderstorms is only 4, as many as 13 have been observed. The shorter days of early fall have lower maximum temperatures due to the gradual reduction of the amount of solar insolation and the forecasting of thunderstorms during the latter part of the thunderstorm season becomes increasingly difficult. For this reason a separate study of September thunderstorms was made in an attempt to set up an objective forecasting aid.

Since an analysis of the upper air was deemed essential for the forecasting of thunderstorms, data for the 6-year period 1940–45, inclusive, were used in the development of the objective aid. This period includes the extremes in number of occurrences, from none during the month to the maximum of 13. A limited amount of 700-mb. data for 1946 was used in the preliminary stages. Raobs were not taken at Denver during 1946, 1947, or 1948. With the resumption of raobs by Lowry Air Force Base, the 1949 and 1950 data became available for test purposes.

THUNDERSTORMS IN THE DENVER AREA

As background for the development of the forecasting aid, the climatology of September thunderstorms and important factors in thunderstorm formation in the Denver area are now discussed.

CLIMATOLOGY

To supplement the information contained in a study of summer thunderstorms (May through September) made by A. W. Cook and the Denver forecasting staff [4], the 20-year period from 1928 through 1947 was studied to determine a few climatological facts about September thunderstorms.

There was a total of 83 thunderstorms during that period which gives an average of but 4.2 each year. The number varied from none in 1944 to 13 in 1940, as shown in figure 1A. Figure 1B shows the departure by years of the monthly mean September maximum temperature from the normal September maximum, and also the departure of the average maximum temperature on days of thunderstorm occurrences. Maximum readings are generally higher on thunderstorm days. There seems to be no relationship between the number of occurrences for the month and the mean maximum temperature for that month. Since September is a transition month between summer and fall, the mean maximum drops sharply from 84.3° F. in August to 64.7° in October with the September mean being 76.5°.

Figure 2 is taken from a previous statistical study [5] in which it was found that nearly all the thunderstorms in the period 1919–38 passed over Denver during the hours from 1200 to 2000 MST. Resultant maximum precipitation amounts in the afternoon and early evening are shown in figure 3. Since September is at the end of the thunderstorm season one might expect to find the curve of occurrences by days of the month (fig. 4) gradually sloping downward to the right, i. e., toward the end of the month. Instead, for the period 1928–47, there was a minimum from the 12th to the 22d, with a maximum near the end of the first week and secondary maxima during the early

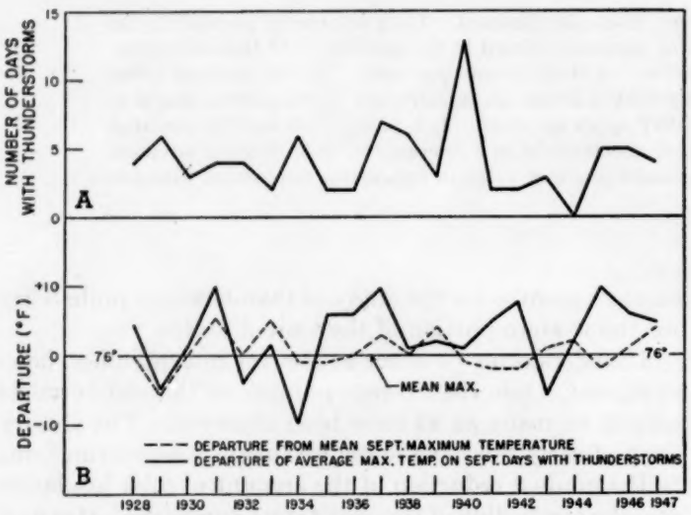

FIGURE 1.—(A) Number of days in September with thunderstorms at Denver, Colo.' by years: 1928–47. (B) Departure of the mean September maximum temperature from the normal September maximum (dashed line), and departure of the average maximum temperature on days in September with thunderstorms (solid line), by years: 1928–47.

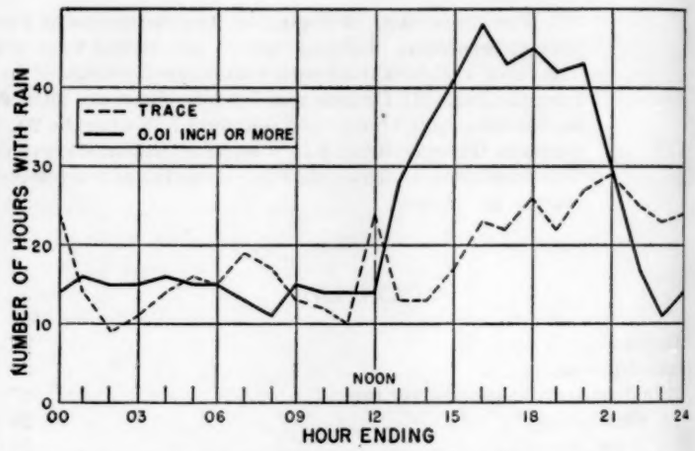

FIGURE 3.—Diurnal distribution of number of hours with rain at Denver, Colo., September 1919–38. (After Cook [5].)

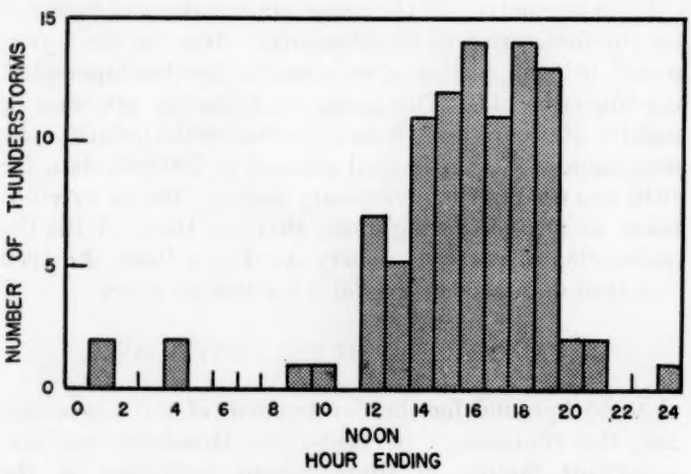

FIGURE 2.—Diurnal distribution of thunderstorms at Denver, Colo., September 1919–38. (After Cook [5].)

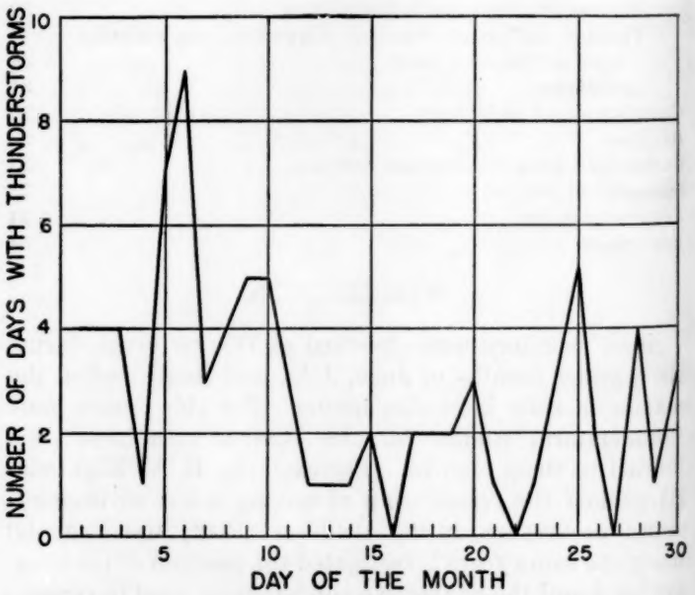

FIGURE 4.—Distribution of thunderstorm days by days of the month, September 1928–47. Total number of days with thunderstorms during the 20-year period was 83.

part of the second and during the fourth weeks. With such a small number of occurrences a few synoptic situations producing several consecutive days of convective activity during any one part of the month would add considerable weight to that portion of the curve. Table 1 shows the frequency of occurrence of thunderstorms on consecutive days.

TABLE 1.—*Frequency of occurrence of thunderstorms on consecutive days Denver, Colo., September 1928–47*

Number of consecutive days	Number of times of occurrence of thunderstorms	Number of times of occurrence of thunderstorms and/or lightning *
1	42	----------
2	15	22
3	2	4
4	0	1
5	1	1
6	0	0
7	0	0
8	0	1

* 1939–47.

FORMATION

The "chimney effect" [4] is generally considered to be of prime importance in the strong convective activity and resultant thunderstorm generation immediately near a range of mountains. The east face of the Rockies is oriented perpendicular to the morning sun and as a result convective currents are set up in the hills and mountains before they are over the plains. The air thus heated over the higher terrain is less dense and rises. This produces a flow in the lower levels up the mountain side which affects the surface winds and the winds in the lower levels at least as far out on the plains as Denver, 40 miles away. Thus it might be said that air lying over the extreme western plains is drawn up the eastern slope of the Rockies which really acts as a steep front with a slope of 1:30. Denver has an elevation of 5,300 feet above sea level while the main range averages about 12,300 feet which gives approximately a 1⅓-mile rise in 40 miles, or a slope of 1 to 30. In this case the air is moving up the stationary surface instead of a moving frontal surface lifting the air, but the result is the same.

In this connection it might be well to point out the importance of Mount Evans, 40 miles west-southwest of Denver. This peak, which is a part of the eastern range of the Rockies, is a pronounced mountain jutting eastward from the range; it is connected to the range by high terrain on the western side only, with the remaining three sides dropping from the elevation of 14,259 feet above sea level down to 7,000 feet in 10 or 12 miles. Solar insolation on the north slopes is quite small, however, very active heating takes place on the eastern and southern slopes. This increases the intensity of the general chimney effect of the main range described above. Forecasters keenly watch the summer convective activity developing over this peak since it appears that these storms are the ones which most often pass over the local Denver area.

A review of the surface charts showed that thunderstorms occur quite frequently from just after a maritime polar frontal passage to as long as two days afterward. The moisture transported into the western plains by the fresh influx of mP air in the lower levels apparently contributes added moisture to increase convective instability and resultant overturning as the air rises up the east face of the Rockies.

Lightning at first was considered to be significant, insofar as visible lightning might be indicative of thunderstorm activity in the general area. However, as stated in a Weather Bureau report [6], "The occurrence of lightning without thunder is not designated as a thunderstorm. The occurrence is reported, of course, but it is not included in the usual summation of thunderstorm days or occurrences. This practice diminishes the area for which a single station can be considered representative of thunderstorm occurrences, the radius of audibility of thunder being much less, ordinarily, than the radius of visibility of lightning. It is also true, however, that the visibility is much greater at night than in the daylight, so that a diurnal variation of frequency based on lightning occurrences would not be representative." Upon investigation it was found that nearly all the lightning at Denver was observed from the northeast through southeast. Nocturnal thunderstorms which so commonly occur over the western Great Plains in the summer can be observed easily from Denver when occurring as far east as the Colorado-Kansas border 150 miles away. Since this type of thunderstorm does not occur in the Denver area, but rather within sight in the east quadrant, lightning was not considered significant, although the data were entered on some of the charts, separate from thunderstorms. Some late evening lightning also occurs over the Continental Divide immediately west of Denver, but storms over the mountains at that time of day nearly always dissipate before reaching Denver.

INVESTIGATION OF VARIABLES

In the development of the forecasting aid, many variables were investigated which were thought to be related to the formation or movement of thunderstorms for this local area. Conditions which existed during the morning of the day of occurrence were studied first. From this study variables were found that should be investigated from similar data for an earlier time; the time lag was chosen so that thunderstorms could be forecast from data available to the forecaster at about midnight. The forecast period was considered to be from midnight to midnight, but for all practical purposes, as shown by the diurnal distribution of thunderstorms in figure 2, the forecast is for afternoon and evening thunderstorms.

WINDS

For summer thunderstorm occurrences at Denver, Cook and the Denver Forecasting Staff [4] found that "at approximately 10,000 feet MSL the direction of winds

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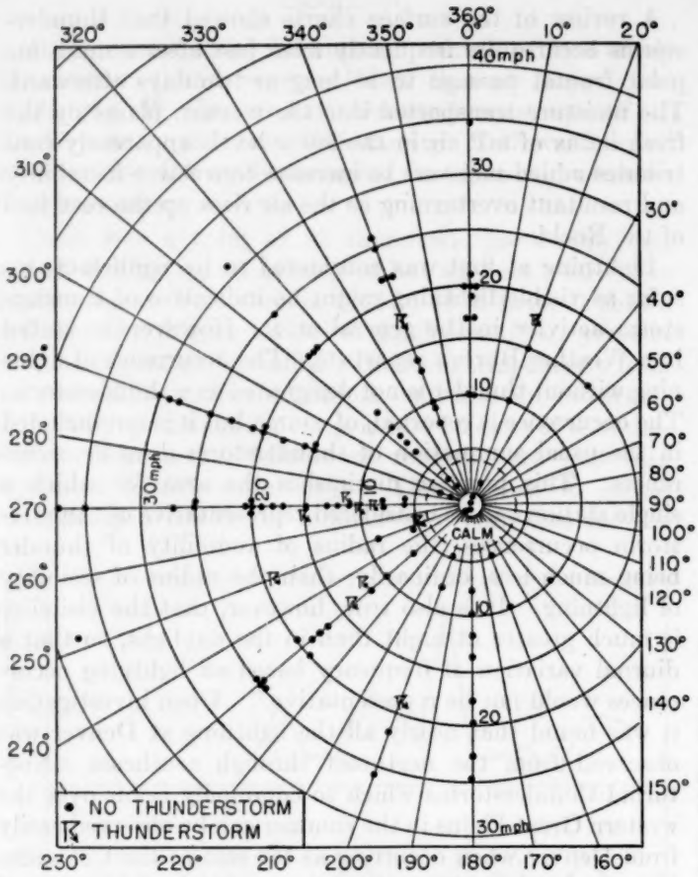

FIGURE 5.—Wind at 700-mb. level at Denver, Colo., 0800 MST daily, September 1943–46, with plotted symbol indicating occurrence of thunderstorm (⚡) or no thunderstorm (•) on the same day.

varied from south clockwise to east-northeast, with southwest and south predominating. The movement of the convective type storm seems to be definitely connected with the winds aloft. In many cases the storms move away from the mountains in a direction comparable to that of the winds at about 11,000 feet MSL. This corresponds to Brancato's findings in the Ohio Valley that thunderstorms move with the speed of the 4–6,000 feet-above-surface winds." Since the elevation at Denver is 5,300 feet, winds 4,000–6,000 feet above the surface would be near the 10,000–11,000-foot MSL level.

The height of the 700-mb. level during September is usually between 10,000 and 10,600 feet, therefore the 0800 MST 10,000-foot or 700-mb. winds at Denver for the 4 years 1943–46 were plotted on polar coordinate paper with thunderstorm occurrence represented by a thunderstorm symbol. See figure 5. Of the winds with velocities above 5 mph., 94 percent were found to be from south through west to north, inclusive. Fifty-three percent were from south to west, inclusive. Sixty-nine percent (9/13) of all thunderstorms occurred with winds southwesterly to westerly, inclusive, which, qualitatively, are the same results as found for the midsummer thunderstorms.

No thunderstorms occurred with southeasterly winds. These winds are produced by a 700-mb. Low over New Mexico, Arizona, or eastern Colorado. Two storms occurred with northerly quadrant winds, but strong cold air advection at upper levels produced unusually unstable lapse rates at higher levels which may account for these.

Wind speeds at 10,000 feet on thunderstorm days were usually 8–20 mph. It is thought that stronger winds tend to tear off the tops of the buildups preventing them from fully developing into cumulonimbi.

700-MB. FLOW

A preliminary study of the 0800 MST 700-mb. flow showed that a general southwesterly to westerly flow over the Denver area seemed to be necessary for occurrence of a thunderstorm at Denver, which is in agreement with the results indicated in the analysis of the 10,000-foot wind in the preceding paragraphs. This flow was found to prevail 62 percent of all days during the two September months investigated, with all thunderstorms occurring when this type of flow existed.

As a simple objective measure of this flow at 2000 MST, the height difference between Denver and Boise was tabulated. This measure of gradient was chosen to the west of Denver to allow for the general easterly movement of the upper air patterns. A large positive value of this difference (Denver minus Boise) indicates a strong southwesterly flow. Table 2 shows the percent frequency of occurrence of thunderstorms in class intervals of the height difference, with higher percentages of occurrence with larger positive values of the difference.

TABLE 2.—*Frequency of occurrence of thunderstorms in class intervals of 700-mb. height difference, Denver minus Boise (September 1940–45)*

700-mb. height difference Denver minus Boise	Total cases	Number of thunderstorms	Percent frequency of occurrence
Tens of feet			
<0	36	1	3
0–5	27	3	11
6–10	36	2	6
11–15	24	5	21
16–20	20	5	25
21–25	17	4	24
>25	16	3	19

AVERAGE MIXING RATIO IN LOWER LEVELS

One method [1] of determing the average mixing ratio in analyzing instability of air uses the moisture in the friction layer, considered to be below the top of the inversion, or if the inversion is destroyed by 1000 MST, the layer 40 mb. above the surface. Another [3] averages values from the surface to the 500-mb. level "bearing in mind that the air below the free convection level will be thoroughly mixed by the time the critical temperature for the day is reached." Much this latter line of reasoning was used in this study when mixing ratio values from the surface through the 700-mb. level were averaged. The average was computed by the formula $\overline{w}=\frac{\Sigma w}{N}$. The convective condensation levels were found to vary from approximately 580 to 670 mb., or 6,000 to 9,000 feet above

TABLE 3.—*Frequency of occurrence of thunderstorms in class intervals of average mixing ratio in layer surface to 700 mb. (September 1940–45)*

Average mixing ratio surface to 700-mb.	Total cases	Number of thunderstorms	Percent frequency of occurrence
gm/kgm			
≤4.0	22	1	4
4.1–5.0	37	0	0
5.1–6.0	43	4	9
6.1–7.0	21	3	14
7.1–8.0	21	5	24
8.1–9.0	16	3	19
9.1–10.0	9	2	22
>10.0	7	5	71

the surface. Since mixing ratio values are not available at any consistent level above 700 mb., for the sake of uniformity no values were used above that level. By using this method moisture was averaged throughout approximately the lower 4,700 feet above ground.

A strong relationship was found to exist between the average mixing ratio at 0800 MST and the occurrence of thunderstorms the same day. The average mixing ratios from the 2000 MST raobs were therefore analyzed; the results are shown in table 3. There was a very marked increase in frequency of occurrence with higher values of the average mixing ratio.

The mixing ratio at 700 mb. alone was also investigated, and, while a relationship existed, it did not appear to be as strong or significant as the relationship between the average mixing ratio and the occurrence of thunderstorms.

PRESSURE DIFFERENCE BETWEEN CONVECTIVE CONDENSATION LEVEL AND FREEZING LEVEL

The 0800 MST raob data were used to determine the relationship of the pressure difference between convective condensation level and freezing level and the occurrence of thunderstorms the same day. Legg [2] used data for the warm summer months, June, July, and August for 1941 and 1942, using a rather shallow layer for determining mixing ratios. Essentially the same results were obtained for September for the 3-year period, 1943, 1944, and 1945, using the average mixing ratio as described above to determine the convective condensation level. During September the mean difference between the condensation level and the freezing level was 57 mb. while Legg found 60. In September the greatest difference was 180 mb. while 140 was the greatest for the summer months. The lowest pressure at which the condensation level was found was the same in both studies, 510 mb., although all but one case in September were below 585 mb. (14,500 ft.).

Only one thunderstorm occurred when the condensation level was significantly higher in elevation than the freezing level, and that occurred when the cold air advection at upper levels was relatively strong, which type of advection lowers the condensation level, assuming no change in the lower levels. Some moisture in the form of liquid drops appears essential for thunderstorm formation.

A similar analysis of 2000 MST raobs for the 6 years 1940–45, inclusive, gave approximately the same results.

TABLE 4.—*Frequency of occurrence of thunderstorms in class intervals of pressure difference between the convective condensation level and the freezing level (September 1940–45)*

Pressure difference	Total cases	Number of thunderstorms	Percent frequency of occurrence
mb.			
<0	103	4	4
0–24	21	4	19
25–49	17	5	29
50–74	16	4	25
≥75	19	6	32

If the condensation level was near or below the height of the freezing level, there was a good possibility of a thunderstorm the following day. Table 4 shows the frequency of occurrence of thunderstorms in class intervals of the pressure difference, a positive value of the difference indicating that the condensation level is below the freezing level. This table also shows a marked increase in the frequency of thunderstorms with greater values of the pressure difference.

INSTABILITY

Considerable analysis was made of a number of years of raobs to find a good objective tool for measuring instability. First, the decrease of pseudo wet-bulb temperature between the levels 850 and 550 mb. was found to be closely related to thunderstorm occurrence. It was found that the probability of occurrence was very small if the decrease between those levels was less than 5° C. This method entailed plotting the raob on a larger adiabatic chart than is now currently used at Denver and also plotting the additional pseudo wet-bulb curve. Table 5 shows how the frequency of occurrence of thunderstorms increases with greater convective instability.

TABLE 5.—*Frequency of occurrence of thunderstorms in class intervals of change of the pseudo wet-bulb temperature from 850 to 550 mb. A negative value indicates a decrease of temperature with height (September 1943, 1944, 1945)*

Change in pseudo wet-bulb temperature from 850 to 550-mb. level	Total cases	Number of thunderstorms	Percent frequency of occurrence
° C.			
>0	21	1	3
0 to −2.4	26	0	0
−2.5 to −4.9	17	0	0
−5.0 to −7.4	11	3	27
−7.5 to −9.9	7	3	43
−10.0 to −12.4	2	1	50
<−12.4	5	0	0

Another measure of the instability is the temperature drop between 800 and 500 mb. This is essentially the same layer as used in the above method, but without moisture being taken into account. Table 6 shows the relationship between this measure of instability at 2000 MST and the occurrence of thunderstorms the following day.

Still another measure of instability is the difference between the surface dew point and the 500-mb. temperature. This measure combines surface moisture with the instability factor described in the preceding paragraph. The

TABLE 6.—*Frequency of occurrence of thunderstorms in class intervals of change of temperature from 800 mb. to 500 mb. (September 1943, 1944, 1945)*

Decrease in temperature from 800 to 500 mb.	Total cases	Number of thunderstorms	Percent frequency of occurrence
° C.			
<20	6	0	0
20–24	8	0	0
25–29	37	3	8
30–34	34	5	15
>34	4	0	0

TABLE 7.—*Frequency of occurrence of thunderstorms in class intervals of temperature difference between surface dew point and 500-mb. temperature. (September 1940–45)*

Difference between surface dew point and 500-mb. temperature	Total cases	Number of thunderstorms	Percent frequency of occurrence
° C.			
<10	17	2	12
11–15	62	2	3
16–20	66	7	11
21–25	28	9	32
>25	3	3	100

dew point used was the one at 2030 MST, synoptic with the raob ascent. Table 7 shows the relationship between this measure of instability at 2000 MST and the occurrence of thunderstorms the following day.

COMBINATION OF VARIABLES

From the variables discussed in the foregoing section three were ultimately combined to form the objective aid for forecasting thunderstorms at Denver. These three were: (1) the height difference at 700 mb. between Denver and Boise, (2) the temperature difference between the surface dew point and the 500-mb. air temperature, and (3) the pressure difference between the convective condensation level and the freezing level. The second variable above was chosen instead of the more theoretically sound "change of pseudo wet-bulb temperature with height" because of its apparent strong relationship to the occurrence of thunderstorms and its simplicity of computation.

Due to the fact that the average mixing ratio from the surface to 700 mb. is used to determine the convective condensation level, there is a high correlation between the average mixing ratio and the pressure difference between the convective condensation level and the freezing level. The average mixing ratio was therefore not used as a separate variable.

There is also, of course, a certain amount of interdependence between the variables 2 and 3 above. The only variable which can be considered as independent of the others is the 700-mb. height difference between Denver and Boise. Essentially the same results are

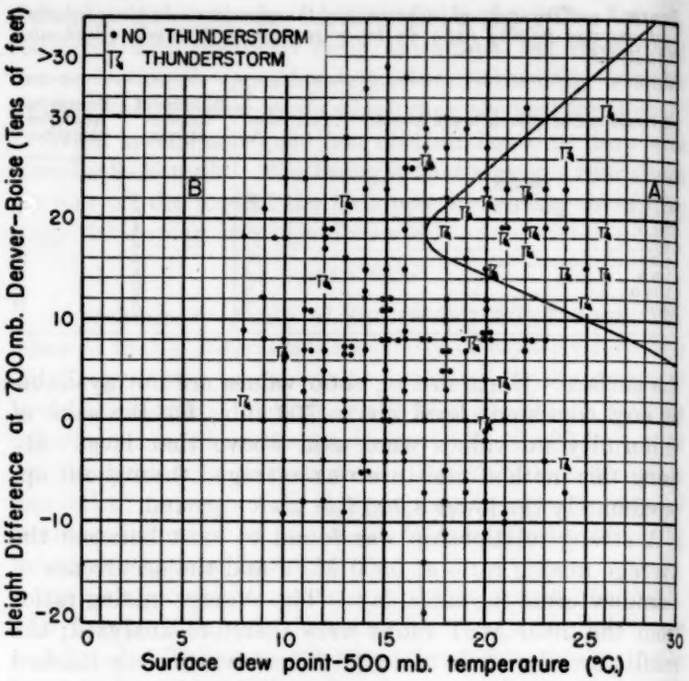

FIGURE 6.—Scatter diagram of thunderstorm (⊓) and no thunderstorm (•) days at Denver, Colo., as related to the 2000 MST height difference at 700 mb. between Denver and Boise and the 2000 MST surface dew point minus 500-mb. temperature at Denver. All cases, September 1940–45.

obtained regardless of the order in which the variables are combined. The two variables which are most readily computed are therefore combined first so that the third variable need not be computed unless the first two show a high probability of thunderstorm occurrence.

In figure 6 the 700-mb. height difference between Denver and Boise is plotted against the temperature difference between the surface dew point and the 500-mb. temperature, with a "no-thunderstorm" day being entered as a dot and a "thunderstorm" day as a thunderstorm symbol.

The best separation of thunderstorm days from no-thunderstorm days is obtained by the line as indicated in figure 6. The reversal of the relationship of the height difference to the occurrence of thunderstorms when the height difference becomes greater than 200 feet tends to bear out the statement made earlier that strong winds aloft tend to tear off the tops of the buildups preventing them from fully developing into cumulonimbi. The separation obtained on this chart is 54 percent (14/26) frequency of occurrence of thunderstorms in the small area delineated by the lines on the chart (area A), and 6 percent (9/143) frequency of occurrence over the rest of the chart (area B). It is of interest to note that of the 12 nonoccurrences in area A, 7 were showers.

The application of the third variable—the pressure difference between the convective condensation level and the freezing level—improves the results only slightly on a *yes* or *no* basis, as it eliminates only two of the nonoccurrences. If the difference is large enough, however, it

TABLE 8.—*Relationship of pressure difference between convective condensation level and freezing level to the frequency of occurrence of thunderstorms for cases falling only in area A of figure 6*

Pressure difference	Total cases	Number of thunderstorm occurrences	Percentage of occurrences
mb.			
<−20	2	0	0
−20 to +80	18	9	50
>+80	6	5	83

RESULTS

increases considerably the probability of getting a thunderstorm, as shown in table 8. A thunderstorm forecast is made if the difference is equal to or greater than −20 mb.

The results of applying the three variables to the original data (1940–45) are summarized in table 9. The skill score is based on the marginal totals of the contingency table.

The test data (1949 and 1950) are summarized in tables 10 and 11. The number of cases is small, but the results tend to bear out the percentages observed in the original data.

TABLE 9.—*Contingency table of "forecasts" of thunderstorms on the original data, September 1940–45*

		Forecast: Thunderstorm	Forecast: No thunderstorm	Total	
Observed	Thunderstorm	14	9	23	Skill score: .54
	No thunderstorm	10	147	157	Percent correct: 89
	Total	24	156	180	

TABLE 10.—*Percentage of occurrence of thunderstorms in the two areas delineated on figure 6. (Test data September 1949 and 1950)*

Area from figure 6	Total cases	Number of thunderstorm occurrences	Percentage of occurrence
A	10	4	40
B	50	4	8

Table 11.—Frequency of occurrence of thunderstorms in class intervals of pressure difference between the convective condensation level and the freezing level. For cases falling in area A of figure 6. (Test data September 1949 and 1950)

Pressure difference	Total cases	Number of thunderstorm occurrences	Percentage of occurrences
<−20	1	0	0
−20 to +80	9	4	45
>+80	0	----	----

COMPARISON WITH CONVENTIONAL FORECASTS

In order to obtain at least an indication of whether the objective aid may prove of use in daily forecasting, a comparison was made with the official forecasts for Denver and vicinity made at about 0230 MST for that day and the following night. Any mention of thunderstorms whatsoever except "thunderstorms along the mountains" was considered a thunderstorm forecast. There can be no argument about a miss being made if thunderstorms are not mentioned in the forecast but one is recorded at the station. However, the argument can be advanced, and perhaps justifiably, that the forecast for Denver and vicinity is for a radius of 20 miles and thunderstorms might well occur in this area which are not heard at the station. This accounts in part for the tendency for forecasting more thunderstorms than are observed at the airport station. However, the same argument can be applied to those days on which the objective method forecasts thunderstorms and none is recorded at the station. On 4 of the 5 days during September 1949 and 1950 on which the objective forecast was for thunderstorms and none occurred, the official forecast also called for thunderstorms. Table 12 shows the contingency tables for the official and objective forecasts for the two test months with the skill scores and percentage correct indicated.

TABLE 12.—*Contingency tables for official and objective forecasts for the test data, September 1949 and 1950*

Official forecasts

		Thunderstorm	No thunderstorm	Total	
Observed	Thunderstorm	3	5	8	Skill score: .14
	No thunderstorm	10	42	52	Percent correct: 75
	Total	13	47	60	

Objective forecasts

		Thunderstorm	No thunderstorm	Total	
Observed	Thunderstorm	4	4	8	Skill score: .38
	No thunderstorm	5	47	52	Percent correct: 85
	Total	9	51	60	

The above comparison is not intended as "proof" of any sort, but it is presented only as an indication that the objective procedures compare very favorably with the forecasts being issued. Two months of independent data are not enough to adequately test any procedure, but the evidence at hand points to the conclusion that this objective aid should prove to be a useful tool in future forecasting of September thunderstorms at Denver. A number of years of use will be necessary to prove or disprove its value as a forecast aid.

SUMMARY OF METHOD

The forecast period for thunderstorm forecasting is from midnight to midnight, which, for all practical purposes as shown by the diurnal distribution, is for after-

noon and evening thunderstorms. The steps taken in making a forecast by this method are:

1. Determine the difference between the surface dew point and the 500-mb. temperature in degrees Centigrade.
2. Determine the height difference (in tens of feet) at 700 mb. between Denver and Boise.
3. Enter figure 6 with values from steps 1 and 2.
4. If the case falls in area A of figure 6 determine the pressure difference in millibars between the convective condensation level and the freezing level.
5. If the value from step 4 is equal to or greater than −20 mb., forecast a thunderstorm; if less than −20 mb., forecast no thunderstorm.
6. If case falls in area B of figure 6, forecast no thunderstorm.

ACKNOWLEDGMENT

The author wishes to convey thanks to Mr. Woodrow Dickey, Research Forecaster, for his valuable assistance in the preparation of this paper.

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THE WEATHER AND CIRCULATION OF FEBRUARY 1951

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The temperature regime in the United States during February 1951 underwent a striking transition during the course of the month, as illustrated in figure 1. The first week was marked by one of the worst cold waves of the twentieth century, as temperatures averaged below normal in nearly all sections, with greatest departures (as much as 23° F.) in the lower Mississippi Valley (fig. 1A). Below-freezing temperatures were recorded at all stations except those in extreme southern parts of Florida, California, and Arizona, and a number of all-time low temperature records were broken in Indiana, Kentucky, and Tennessee. During the second week of the month (fig. 1B) temperatures remained below normal in the East but moderated sharply in the West. In some of the Rocky Mountain States average temperatures for the week were more than 25° higher than in the previous week, and daily maximum temperatures reached record levels on February 10. February's third week was marked by unseasonable warmth throughout eastern and northern portions, but temperatures averaged slightly below normal in most of the Southwest (fig. 1C). By the last week of the month temperatures were above normal in all parts

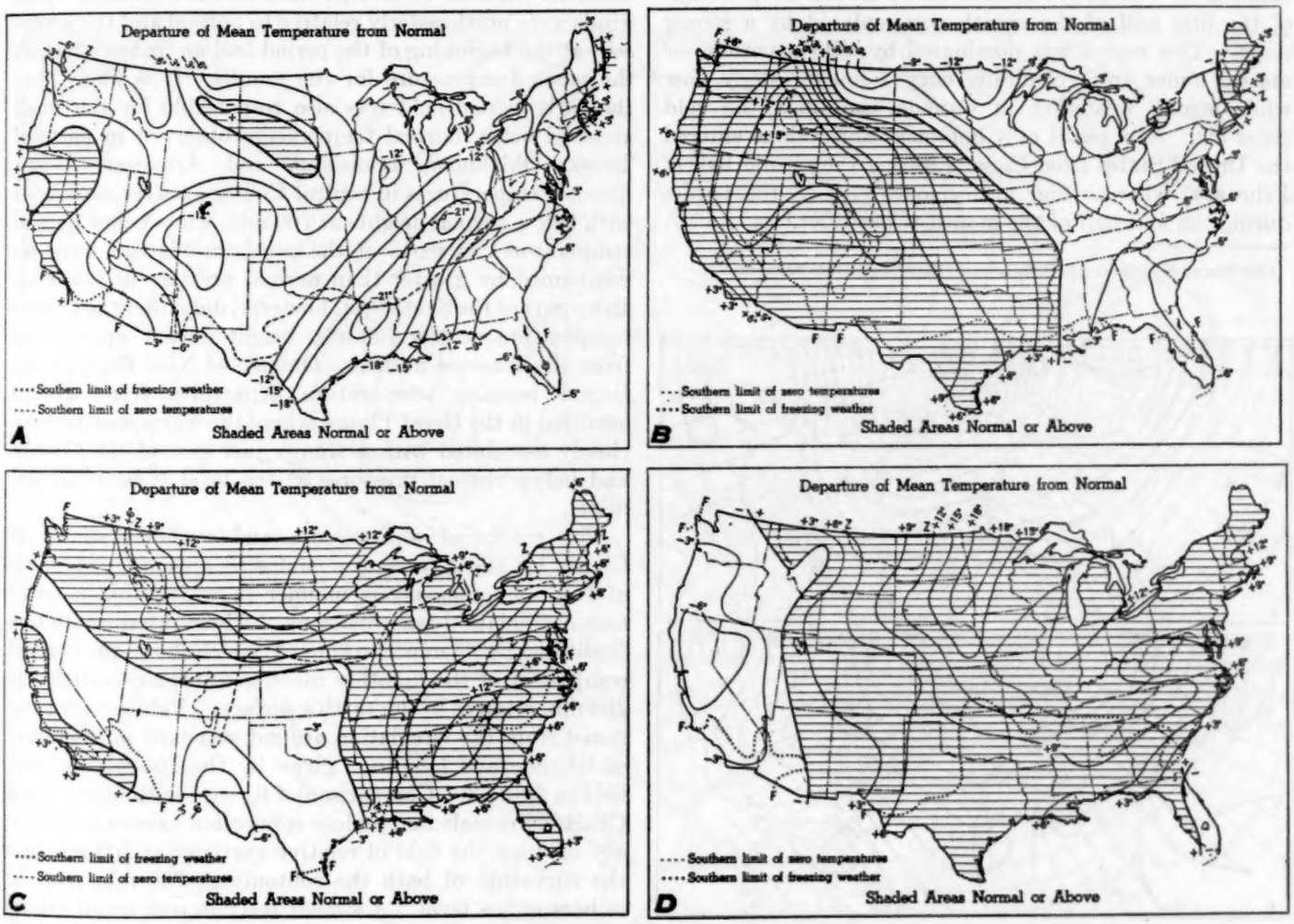
Departure of Mean Temperature from Normal
Southern limit of freezing weather
Southern limit of zero temperatures
A
Shaded Areas Normal or Above
Departure of Mean Temperature from Normal
Southern limit of zero temperatures
Southern limit of freezing weather
B
Shaded Areas Normal or Above
Departure of Mean Temperature from Normal
Southern limit of freezing weather
Southern limit of zero temperatures
C
Shaded Areas Normal or Above
Departure of Mean Temperature from Normal
Southern limit of zero temperatures
Southern limit of freezing weather
D
Shaded Areas Normal or Above

FIGURE 1.—Charts showing departure from normal of the weekly mean temperatures during the month of February 1951; (A) week ending February 6, (B) week ending February 13, (C) week ending February 20, (D) week ending February 27. (Reprinted from Weekly Weather and Crop Bulletin for above dates.)

of the country except the far West (fig. 1D). Thus the temperature regime which prevailed early in February had been completely reversed by the end of the month.

This reversal of the surface temperature pattern was accompanied by an equally striking reversal of the circulation pattern. The mean 700-mb. maps for the first and second halves of February 1951 are presented in figure 2. During the first half of the month a deep full-latitude trough was located in the east-central portion of North America (fig. 2A). This trough was filled with cold polar air carried far southward from strong northerly flow in western Canada and the Arctic Ocean. At the same time the far West was dominated by mild Pacific air transported by strong southwesterly flow off the coast into a well developed ridge in the Great Basin. During the second half of the month, on the other hand, a deep trough was located along the entire Pacific coast of North America (fig. 2B). Strong northwesterly flow between this trough and a well marked eastern Pacific ridge kept temperatures below seasonal normals in the far West. East of the Continental Divide, however, temperatures climbed to well above normal levels as the deep trough of the first half of the month was replaced by a strong ridge. This region was dominated by mild maritime air masses under anticyclonically curved southwesterly flow while strong westerlies in Canada contained the cold polar air. As a result only one polar anticyclone entered the United States from Canada during the second half of February, whereas four anticyclones crossed the border during the first half of the month (Chart IX).[1]

[1] See charts I–XV following p. 44, for analyzed climatological data for the month.

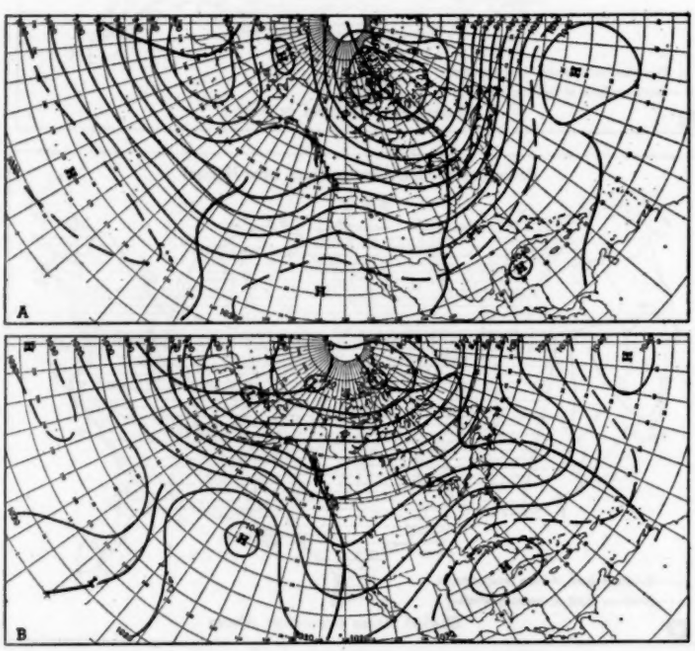

FIGURE 2.—15-day mean 700-mb. charts for (A) January 30–February 13, and (B) February 14–28, 1951. Contours at 200-ft. intervals are shown by solid lines, selected intermediate contours at 100-ft. intervals by dashed lines, and minimum latitude trough locations by heavy solid lines.

Despite the heterogeneous nature of this February's weather the average temperature and circulation anomalies for the month as a whole are in fairly good agreement. Chart I (inset) shows that surface temperatures averaged above normal in most of the country but slightly below normal in limited areas of the South and West. Correspondingly, figure 3 shows that monthly mean 700-mb. heights were above normal in all parts of the United States except in the far West. Moreover, the mean geostrophic air flow relative to normal was from a southerly direction in most of the country at both 700 mb. (fig. 3) and sea level (Chart XI inset). This flow was easterly, however, along the entire eastern seaboard. Since the land is normally colder than the ocean in this area in winter, this transport of excessive maritime Atlantic air was responsible in part for surface temperatures averaging above normal in the East. The maximum temperature anomaly, more than 6° F., was observed in New England, where the positive 700-mb. height anomaly was greatest and the air flow, relative to normal, from the southeast. On the other hand, temperatures were below normal in Florida and southern portions of Georgia and South Carolina, where winds were northeasterly relative to normal and the severe cold at the beginning of the period had an undue effect on the mean temperature for the month. It is likely that the early period cold was also responsible for the small areas of below normal temperature observed in parts of Texas, Oklahoma, Louisiana, and Arkansas. Below normal temperatures in central California were associated with below normal heights at 700 mb., while below normal temperatures in parts of the southern Plateau were accompanied by greater than normal pressure at sea level. In no part of the Southwest, however, did either the surface temperature or the 700-mb. height depart appreciably from the seasonal normal. Outside of New England the largest positive temperature departures from normal occurred in the Great Plains, where the warm weather was closely associated with a trough just east of the Divide, and below normal pressures at sea level (Chart XI and inset).

The tracks of anticyclones and cyclones shown in Charts IX and X present a confusing appearance because of the nonhomogeneous manner in which this month's mean circulation was made up. Their interpretation is facilitated by reference to figure 4, which shows the vertical component of the monthly mean geostrophic vorticity at 700 mb. relative to the earth's surface. Values were computed from the circulation around standard intersections of latitude and longitude given by the 700-mb. contour field in figure 3. Comparison of figure 4 with figure 3 and Chart XI reveals that a close connection existed in February between the field of relative vorticity at 700 mb. and the curvature of both the contours at 700 mb. and the isobars at sea level. A similar relation was noted during January 1951 (see article on the Weather and Circulation in January 1951 Monthly Weather Review). During both months several cells of high and low pressure at sea

level which appeared merely as open waves in the 700-mb. contour pattern regained their cellular character when the field of relative vorticity at 700 mb. was analyzed. Since most of these vortices showed little horizontal displacement with increasing elevation, the field of relative vorticity at 700 mb. may prove to be a useful index of the sea level circulation, at least for monthly means.

The anticyclone tracks (Chart IX) are clustered in regions where anticyclonic vorticity at 700 mb. was superimposed on high pressure at sea level, namely, the northeast and southeast Pacific, northwest Canada, southeast United States, and the central Atlantic (and the Great Basin to a lesser extent). In these areas anticyclones tended to stagnate and intensify but cyclones were relatively infrequent (Chart X). On the other hand, the conspicuous absence of anticyclones near Bermuda and near the west coast, where they normally abound, was related to the presence on the mean charts of cyclonic vorticity in the troughs at 700 mb. and sea level. This distribution of cyclones and anticyclones can be cited to explain the marked deficiency of precipitation observed throughout the southeast United States in February. In much of this section less than half of the normal precipitation (Chart III–B) and less than one inch of snow (Chart IV) fell during the month while sunshine (Chart VII–B) and solar radiation (Chart VIII inset) were both excessive. However, a corresponding deficiency of cloudiness (Chart VI–B) was not observed, probably because of the abundance of high clouds on the periphery of cyclonic disturbances passing northwest of the area. It is interesting to note that snowfall was excessive in parts of Louisiana, Mississippi, Tennessee, and Kentucky (Chart V–A) despite subnormal precipitation because of early period storminess.

Chart X shows that cyclones were frequent in the Bering Sea, Great Plains, Hudson Bay, Baffin Bay, Denmark Strait, Labrador, and off the east and west coasts of North America. Each of these seats of cyclonic activity was characterized by the presence of cyclonic vorticity at 700 mb. and low pressure or troughs at sea level. The cyclone tracks between these centers generally followed the mean 700-mb. steering flow along the

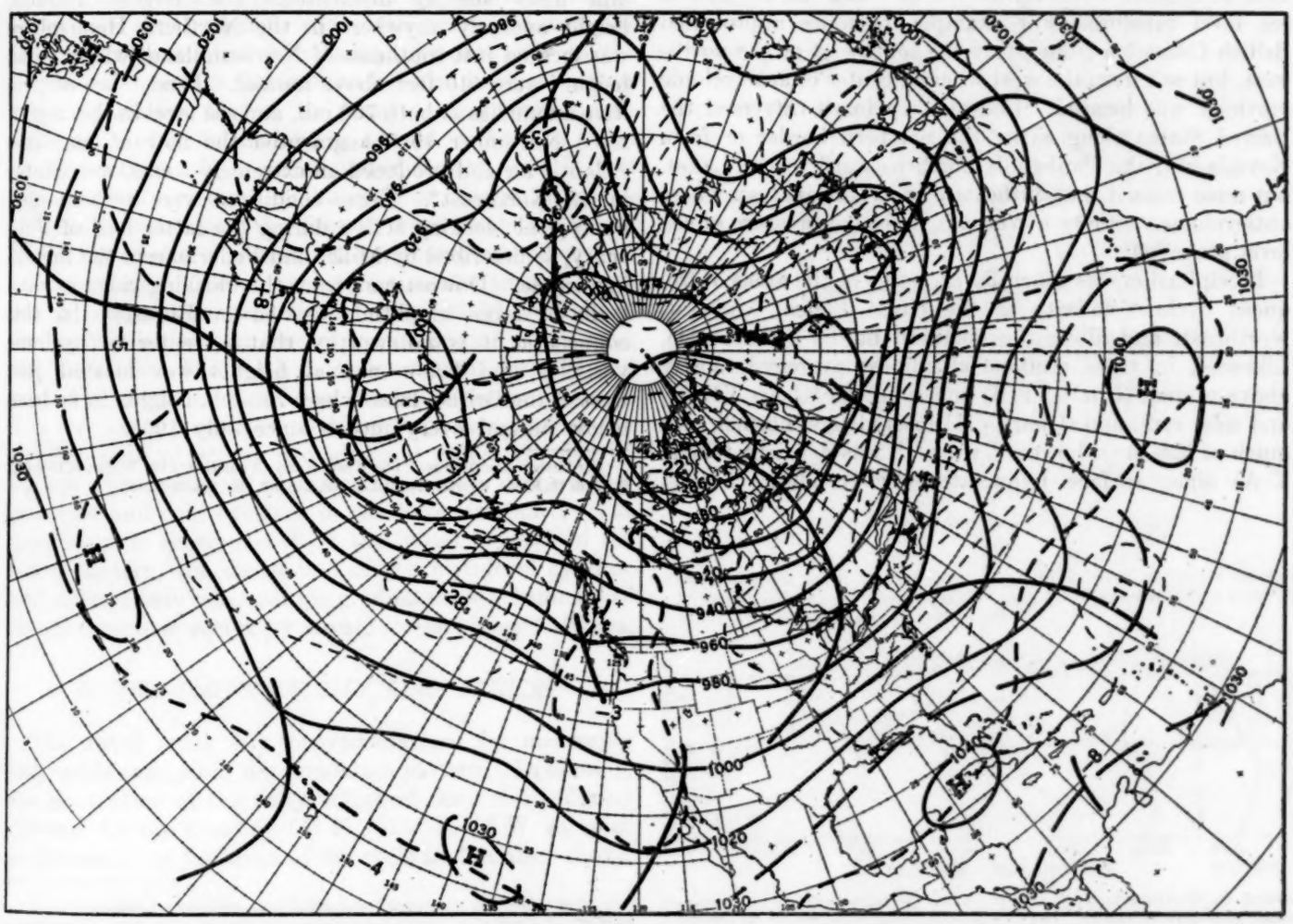

FIGURE 3.—Mean 700-mb. chart for the 30-day period January 30–February 28, 1951, inclusive. Contours at 200-ft. intervals are shown by solid lines, intermediate contours by lines with long dashes, and 700-mb. height departure from normal at 100-ft. intervals by lines with short dashes with the zero isopleth heavier. Anomaly centers and contours are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

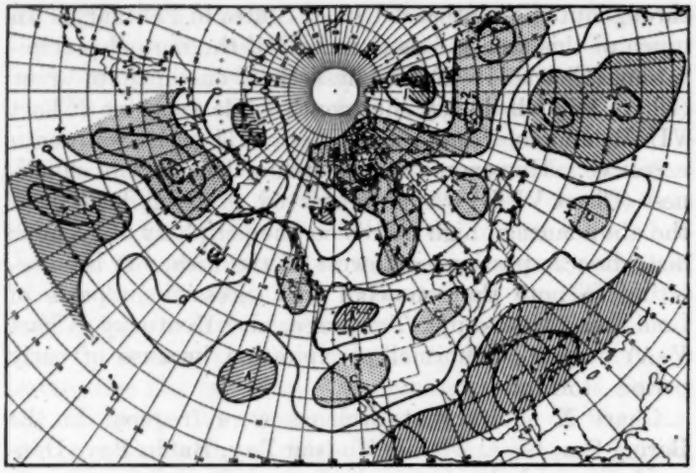

FIGURE 4.—Vertical component of mean relative geostrophic vorticity at 700 mb. for the 30-day period January 30-February 28, 1951. Areas with cyclonic vorticity in excess of 1×10^{-5} per second are stippled and labeled C at the center; areas with anticyclonic vorticity less than -1×10^{-5} per second are cross hatched and labeled A at the center.

axes of cyclonic vorticity at 700-mb. and the troughs of sea level pressure. For example, cyclones approached British Columbia from either the southwest or the northwest, but not from the west where a center of anticyclonic vorticity was located. Likewise, cyclones traversed the United States along either the northern border or from Nevada and the Panhandle northeastward to the Lakes, but none crossed the southeast or northern plateau where anticyclonic vorticity at 700 mb. and high pressure at sea level prevailed.

Precipitation was generally excessive in the areas of frequent cyclone activity in the Great Plains, Midwest, Northeast, and along the northern border (Chart III). Likewise, in these sections cloudiness averaged mostly above normal (Chart VI–B) and sunshine (Chart VII–B) and solar radiation (Chart VIII inset) below normal. In much of this area, however, snowfall was deficient (Chart V–A) since surface temperatures were above normal (Chart I inset). This unseasonable warmth, particularly at the end of the month, was responsible for the fact that all but mountain and northern border areas of the country were free of snow cover on February 27 (Chart V–B), despite the fact that appreciable snow had fallen during the month (Chart IV).

The principal regions of deficient precipitation, in addition to the Southeast, were the Southwest, where a center of above-normal sea level pressure was located (Chart XI inset), and the area adjacent to the Black Hills of South Dakota, where relative vorticity at 700 mb. was anticyclonic (fig. 4). No measurable precipitation at all was recorded in some of these sections (Chart II), and snowfall was generally subnormal (Chart V–A) and sunshine excessive (Chart VII–B). Cloudiness, however, generally averaged above normal (Chart VI–B) and was probably either scattered or of the high thin type.

The heterogeneous nature of February's weather was reflected in the fact that the observed 700-mb. mean map for the month as a whole contains four separate and weak trough segments in the vicinity of North America (fig. 3). Elsewhere, the mean circulation was simpler and more sharply delineated. The largest 700-mb. height anomaly anywhere in the Northern Hemisphere was located just southeast of Newfoundland, where mean heights were 510 feet above normal. Persistence of positive anomalies at both 700 mb. and sea level in this region since November 1950 augmented the flow of maritime Atlantic air and produced an extremely warm, wet winter in the Northeast*. These conditions were accompanied by typical blocking action during the latter half of February, as described by Miller and Vederman in the following article. Downstream from the blocking ridge a wave train of large amplitude existed in Eurasia. In this connection it is noteworthy that a center of cyclonic vorticity and below normal heights was located just west of the British Isles, where 700-mb. heights have been below normal every month since July 1950.

* For further discussion see "The Weather and Circulation of the Winter of 1950–51," William H. Klein, *Weatherwise*, vol. 4, No. 2, April 1951, pp. 38–39, 46.

BLOCKING ACTION OVER THE NORTHEAST DURING THE LATTER HALF OF FEBRUARY 1951

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INTRODUCTION

The development and effects of blocking action in broad-scale circulation patterns have been the subject of several recent investigations [1, 2, 3, 4]. Such "blocks" are frequent during the month of February, a period of the year that is favorable for the maintenance of warm anticyclones in northerly latitudes and cold cyclones in southerly latitudes [1]. This article discusses blocking action that began in the western Atlantic after mid-February 1951 and the associated effects on the movements of storms over the eastern half of the United States.

Blocking action [1] is characterized by the breakdown of essentially zonal motion into more cellular motion [3]. The importance of such a change lies not only in the altered flow pattern that results but also in the tendency for the cellular pattern to persist and remain quasi-stationary, often for as long as several weeks. In terms of fluctuations of the zonal index Rossby and Willett [5] describe four stages in the cycle of changes from one pattern to another. The first of these stages is that of initial high index characterized by, among other features, an expanding and strengthening jet stream located north of the normal seasonal latitude. The initial lowering of the high-index pattern occurs in the second stage after the jet stream has reached its maximum strength and moved near or south of the normal seasonal latitude. The low index pattern of the third stage brings about the development of strong troughs and ridges in the jet stream with cutting off of warm anticyclones in the higher latitudes and cold cyclones in the lower latitudes. The final stage is accompanied by the initial increase of the index pattern, the dissipation of the high-level cyclonic and anticyclonic cells, and the gradual re-establishment of the circumpolar vortex jet stream in the higher latitudes.

DEVELOPMENT OF BLOCKING ACTION

The zonal index is a convenient tool for measuring large-scale changes in the circulation pattern. In figure 1, the fluctuation of the daily values of the zonal index at 700 mb. for the area 35°–55° N., 175° E.–5° W. serve as an indication of the stage of the cycle as described above. The initially high index prior to February 18 corresponds to stage one, the transitional falling period from February 18 to 22 is characteristic of stage two, while the period from February 23 to the end of the month (and well into the month of March) could be classified as stage three.

A more detailed picture of what occurred during the latter half of the month can be obtained from the 3-day mean profiles of zonal speed at 600 mb. for the area 135° W.–20° W., presented in figure 2. In the first curve the maximum at 50°–55° N. was somewhat stronger than normal and displaced far north of its normal seasonal position, a condition indicative of stage one. The pres-

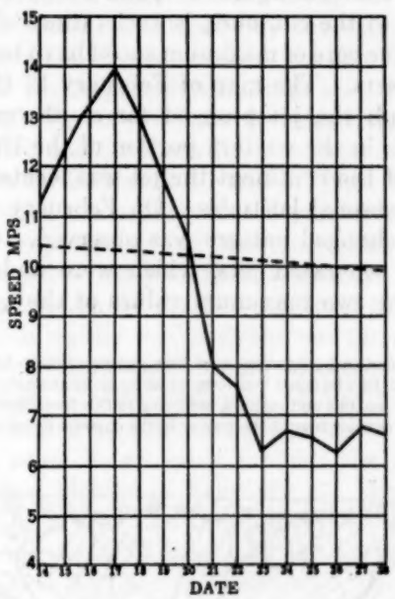

FIGURE 1.—Daily values of the 700-mb. zonal index in meters per second for area 35°–55° N., 175° E.–5° W. Dashed line represents February mean. (Data provided by Extended Forecast Section, Weather Bureau).

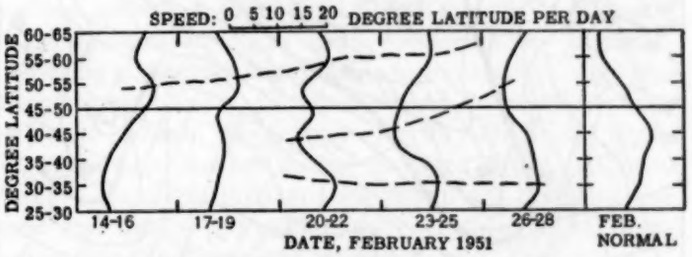

FIGURE 2.—Three-day mean profiles for 1500 G.M.T. of zonal wind speed at 600 mb. for area 135° W.–20° W. Curve on right is mean for February. Dashed lines represent trends of maximum and minimum values. (Data provided by U. S. Air Force.)

[1] Rex [2] discusses the initiation, development, and dissipation of blocking in terms of a proposed physical mechanism which is analogous to a "jump" in hydraulic flow in open channels.

ence of only one maximum and one minimum was normal for the season [5] but the pronounced minimum at 30°–35° N. represented a considerable deviation from the mean curve for February. Beginning with the curve of February 17–19 there was strong evidence that a change in circulation was evolving. On the days represented by that curve and thereafter there were generally present at least two maxima, as is especially evident from the curve of February 23–25. The two definite maxima that existed on those days, one at very low latitudes and the other at extremely high latitudes, were located at the same positions where minima existed approximately 10 days before. At the same time the minimum value was located precisely where a maximum is normally found. The migration of this minimum value[2] was associated with the northward migration of warm anticyclones. This effect of a split jet stream with the northern branch moving toward higher latitudes while the southern branch moves southward is one of the characteristics of blocking action [2].

In order to illustrate the splitting of the jet stream in more detail, with its resultant decrease in the zonal index, the 300-mb. charts of figures 3, 4, and 5 have been selected. In addition to the contours, isotachs (lines of equal wind speed) and the core of maximum speed have been indicated on these charts. The map of February 13 (fig. 3) shows that although the jet plunged far southward around a sharp trough in the western portion of the United States, over most of the continent the jet was located well north of normal seasonal latitudes. On February 17 (fig. 4) a completely changed pattern was observed. On that day two widely separated jets, which were undoubtedly reflected in the two maximum values of the zonal profiles,

[2] The occurrence of such migrations over long periods seems to be suggested by the work of Riehl et al. [6] who found long term trends in momentum changes in the westerlies. Momentum maxima and minima, according to this investigation, either progress steadily from the equator toward the pole or in the opposite direction.

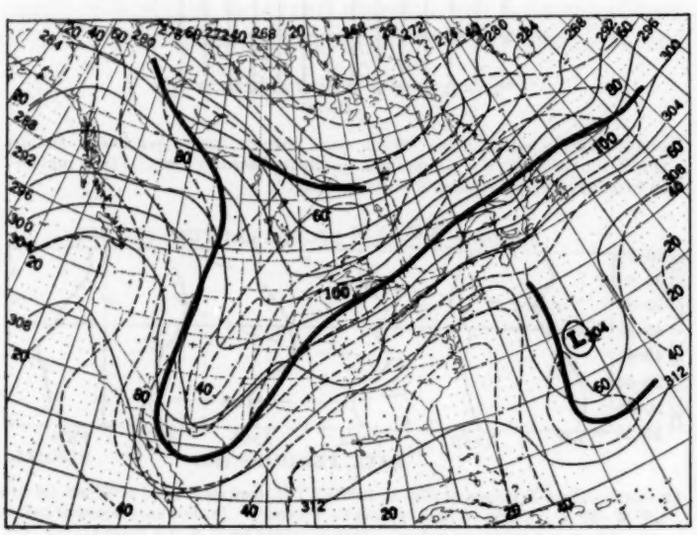

FIGURE 3.—300-mb. chart for 1500 GMT, February 13, 1951. Contours (solid lines) at 400-ft. intervals are labeled in hundreds of geopotential feet. Dashed lines represent isotachs (lines of equal speed) at intervals of 20 knots. Heavy line represents jet stream.

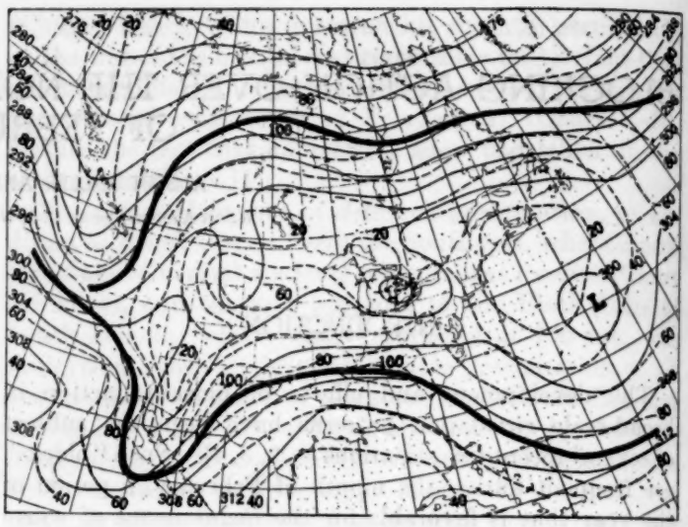

FIGURE 4.—300-mb. chart for 1500 GMT, February 17, 1951.

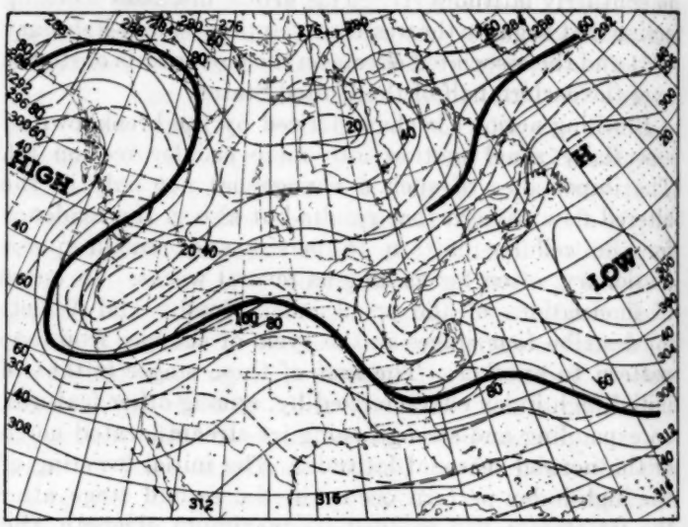

FIGURE 5.—300-mb. chart for 1500 GMT, February 21, 1951.

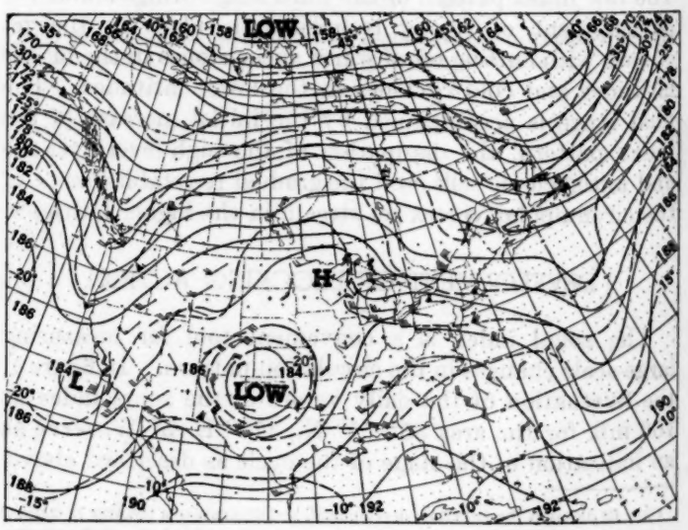

FIGURE 6.—500-mb. chart for 1500 GMT, February 15, 1951. Contours (solid lines) at 200-ft. intervals are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are at intervals of 5° C. Barbs on wind shafts are for speeds in knots (pennant =50 knots, full barb=10 knots, and half barb=5 knots).

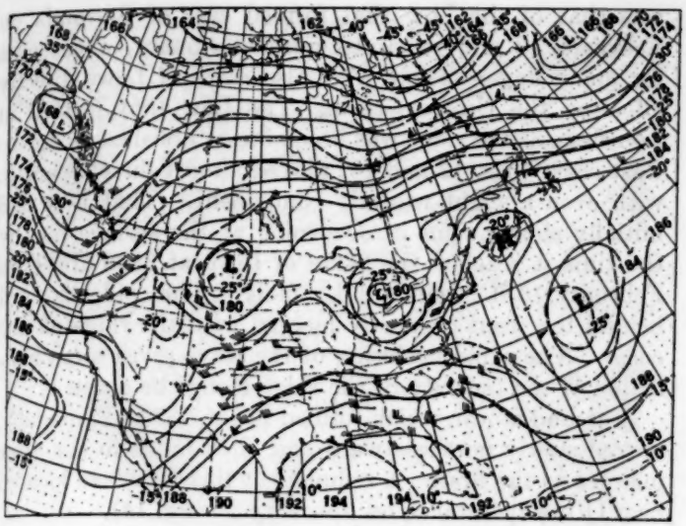

FIGURE 7.—500-mb. chart for 1500 GMT, February 17, 1951.

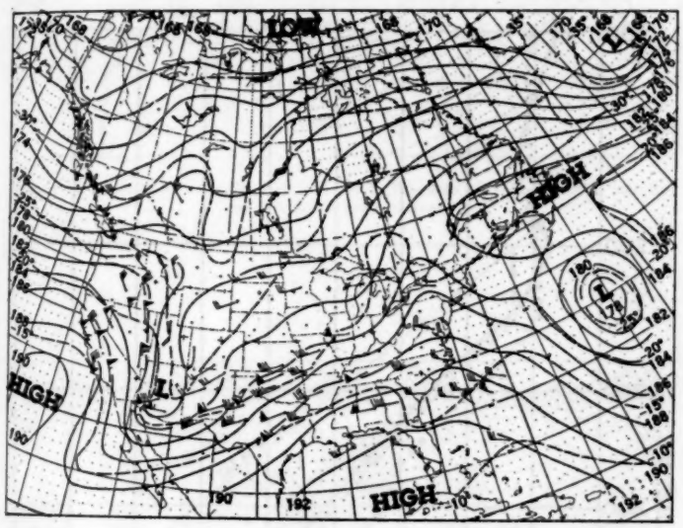

FIGURE 8.—500-mb. chart for 1500 GMT, February 19, 1951.

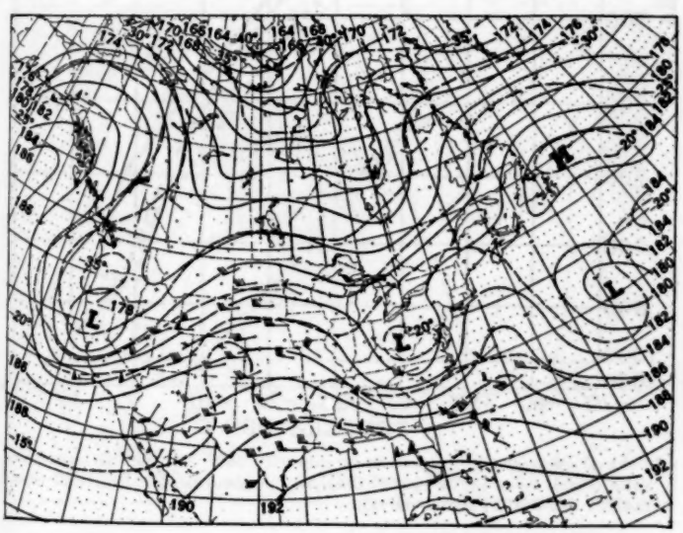

FIGURE 9.—500-mb. chart for 1500 GMT, February 21, 1951.

appeared over most of North America. By February 21 (fig. 5), the most northerly jet had weakened appreciably (also observed in fig. 2), although the southern branch persisted with little change. Concurrent with the wide breaching of the jet was the development of the ridge over Nova Scotia.

Another characteristic of blocking is its persistence. The continuous trends that can be seen in figures 1 and 2 illustrate this effect to some extent, although the period covered by the curves is relatively short.

THE QUASI-STATIONARY RIDGE ALONG THE NORTHEAST COAST

The anticyclone that became almost stationary over New England (fig. 12) originated as a polar outbreak from northwest Canada. Throughout the period under discussion its central pressure value slowly decreased. The warm anticyclone that existed at 500 mb. directly above the surface center on February 17 (figs. 7 and 13) had migrated from the west. After the surface and upper level positions coincided there was very little motion of the centers at any level. An illustration of the decreased temperature gradient that resulted along the east coast after the area became dominated by the extensive warm ridge and the zonal flow decreased, can be seen from a comparison of the upper-air soundings at the stationary ship "H" (36° N., 70° W.), Sable Island, Nova Scotia (44° N., 60° W.), and Stephenville, Newfoundland (48° N., 58° W.) taken on February 15 and 19 (figs. 10 and 11). Of interest also is the cooling that occurred in the upper levels of the troposphere and the stratosphere at these three stations, particularly marked at Stephenville.

The first indication at the 500-mb. level (figs. 6 to 9) that a change in regime was evolving was the appearance of a cold, "cutoff" Low on February 14 centered over the Texas Panhandle. After February 14 the flow pattern over North America rapidly changed to one of low index although the zonal index value for half the hemisphere (fig. 1) remained high until February 17. By February 17 (fig. 7), another cold Low developed over the Atlantic Ocean to the northeast of Bermuda and persisted in approximately the same position for 5 days. Northwest of this Low, a well-developed ridge just off the coast had decelerated markedly and had become almost stationary. New "cutoff" Lows continued to develop over the midwestern portion of the United States and move eastward or northeastward. Each had a similar history of initial deepening and subsequent filling as it neared the ridge line along the east coast. It was not until February 24, that a Low at 500 mb. which formed in Virginia finally penetrated the coast line and moved eastward into the Atlantic Ocean. However, it stagnated within 150 miles of the coast and finally proceeded slowly northeastward, dissipating over Newfoundland on February 27.

The ridge along the east coast did move eastward after February 21 but that did not signify the end of blocking

action affecting the North American continent. The blocking action merely appeared to be displaced upstream. Following this period a well-developed ridge dominated the eastern half of the United States for several days and, near the end of the month, another great ridge formed along the Pacific coast of the continent.

EFFECT OF BLOCKING ACTION ON SURFACE CYCLONES

The normal track of cyclones that form or move into the eastern United States or the western Atlantic is toward the northeast [7]. They also tend to deepen as they move toward higher latitudes. During the period of blocking action, however, the storms that appeared deviated considerably from normal.

One case of great deviation in the behavior of cyclones was that of the Low that formed east of Bermuda on February 13 and remained quasi-stationary in the area for many days. There were also cases of Lows directly affecting the United States. The Low that formed in Louisiana as the ridge was becoming established along the East coast (figs. 12 and 13) moved almost directly north, with even a slight westerly component. That Low had initially shown signs of deepening at the surface but by the time it reached the State of Iowa at 1830 GMT on February 16 it began to fill rapidly. The cold High cell behind the front gradually merged with the ridge off the coast. The rapid occlusion of the wave gives some indication of the tenacity of the ridge along the coast.

A second storm, which formed in the Texas Panhandle, moved slowly northeastward and filled much in the same manner as the first. A remnant of this Low was located near Ottawa, Ontario, on February 20 (fig. 14).

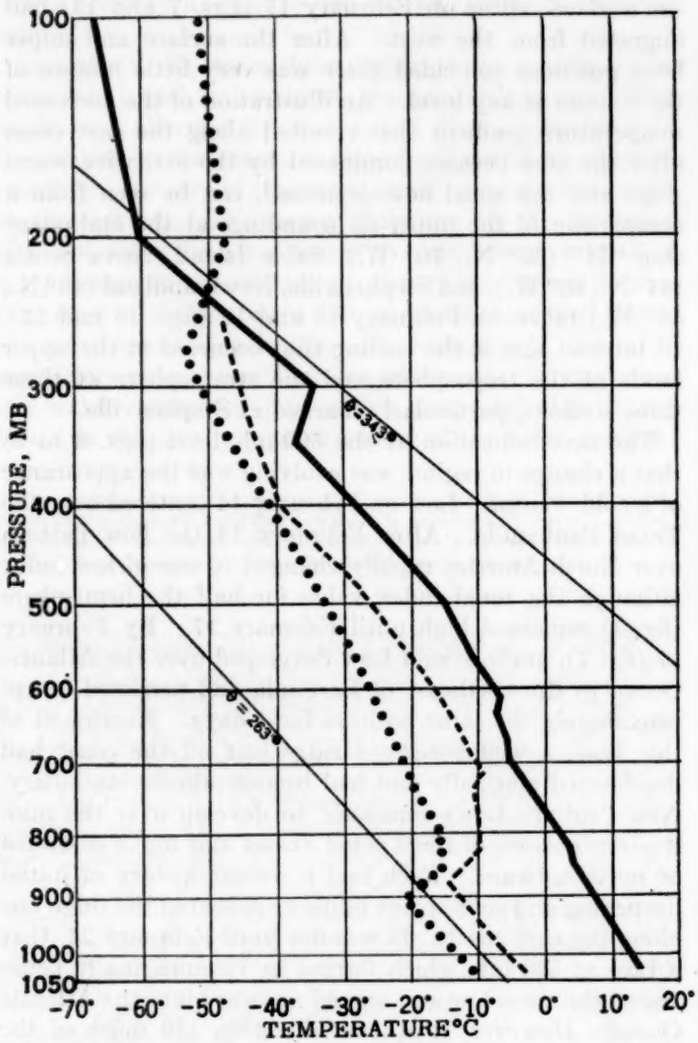

FIGURE 10.—Radiosonde observations at ship "H" 36.0° N., 70.0° W. (solid line), Sable Island, Nova Scotia (dashed line), and Stephenville, Newfoundland (dotted line), for 1500 GMT, February 15, 1951.

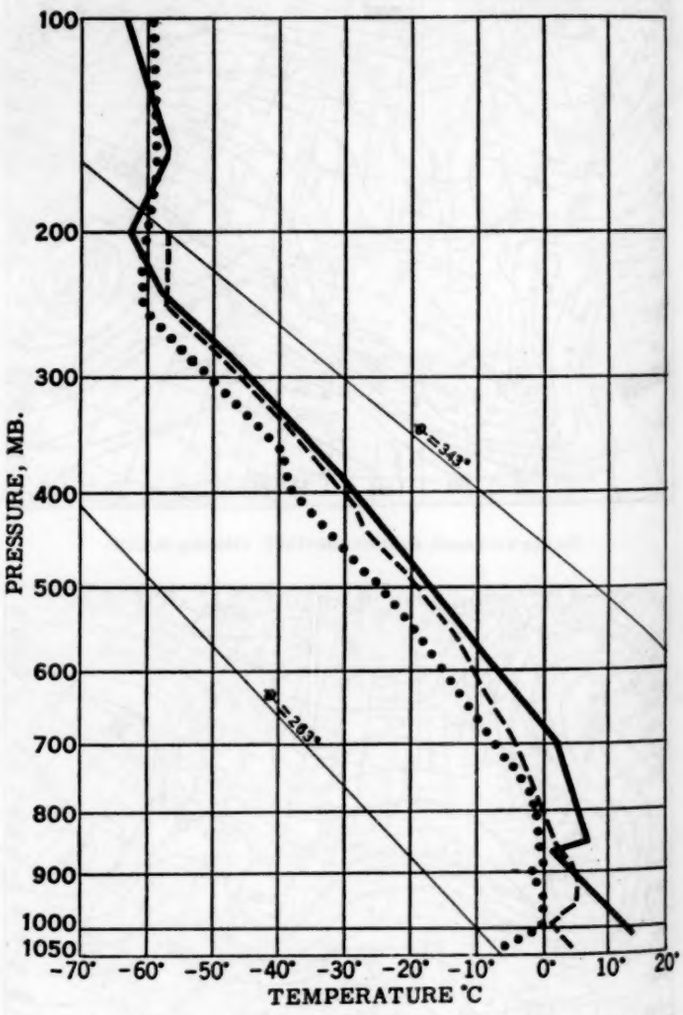

FIGURE 11.—Radiosonde observations at ship "H" 36.0° N., 70.0° W. (solid line), Sable Island, Nova Scotia (dashed line), and Stephenville, Newfoundland (dotted line), for 1500 GMT, February 19, 1951.

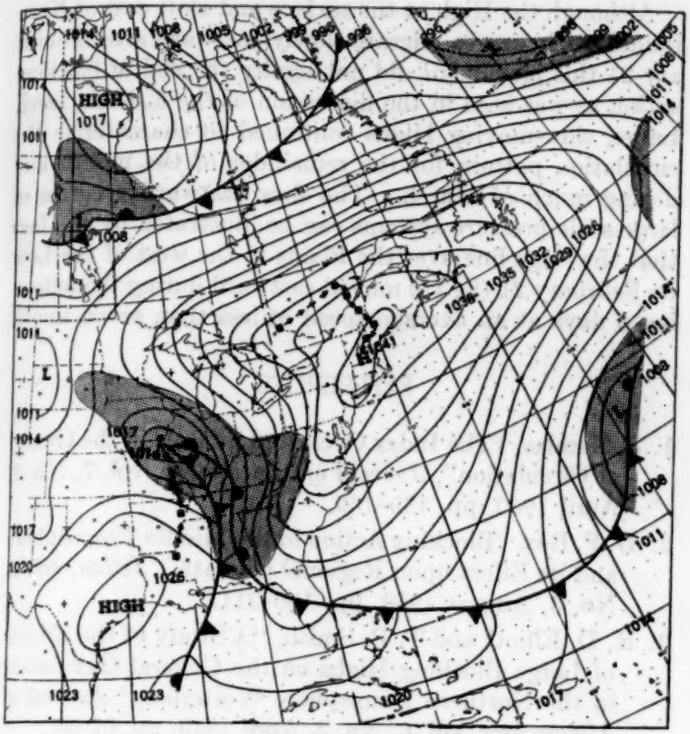

FIGURE 12.—Surface weather chart for 1230 GMT, February 16, 1951. Shading indicates areas of active precipitation.

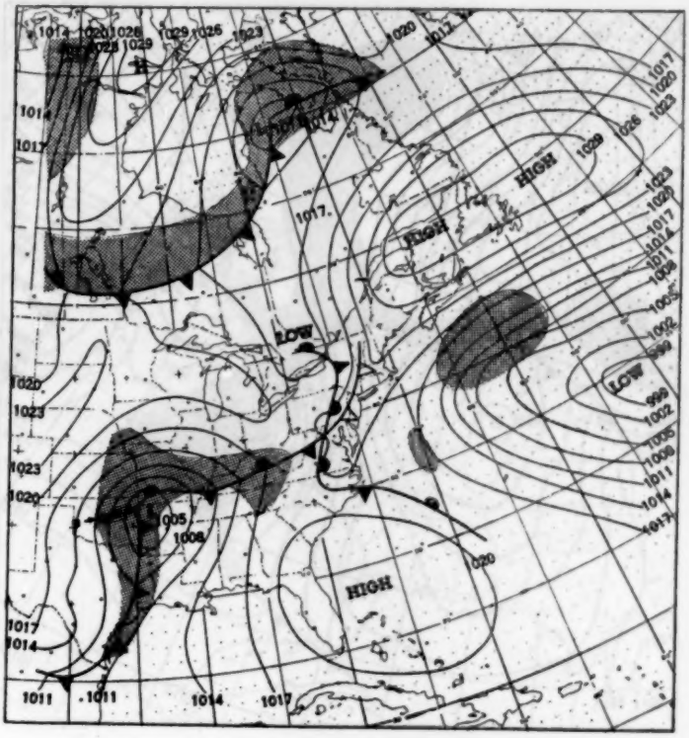

FIGURE 14.—Surface weather chart for 1230 GMT, February 20, 1951.

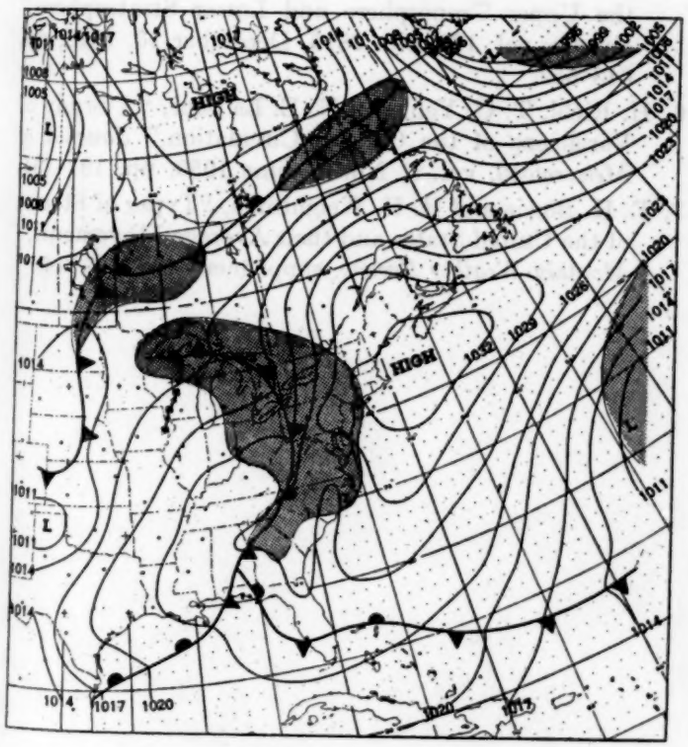

FIGURE 13.—Surface weather chart for 1230 GMT, February 17, 1951.

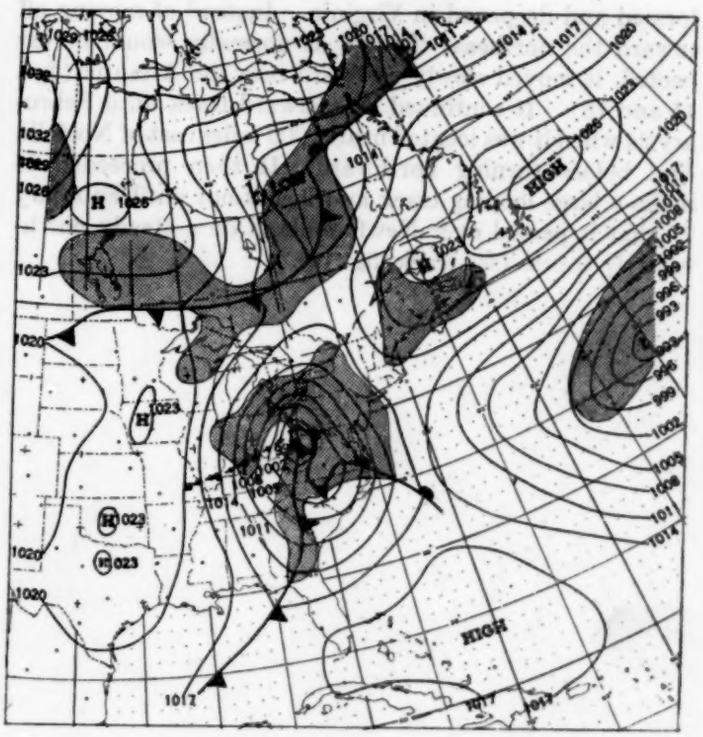

FIGURE 15.—Surface weather chart for 1230 GMT, February 21, 1951.

940551—51——2

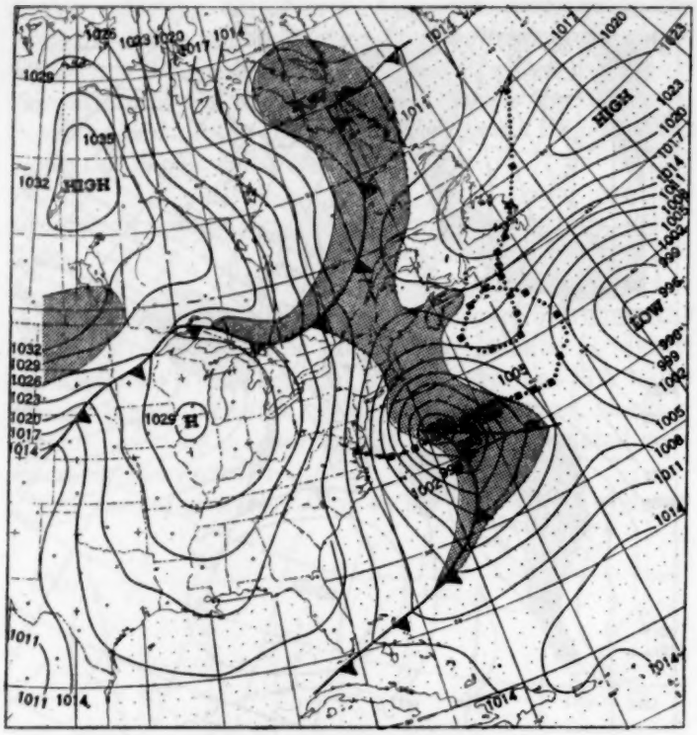

FIGURE 16.—Surface weather chart for 1230 GMT, February 22, 1951.

The cyclone located over western Arkansas in figure 14 had a slightly different history. It moved east-northeastward into western Pennsylvania where it filled rapidly. However, a new Low to the south of the dissipating storm formed and deepened in Virginia. Instead of moving off toward the northeast though, as normally would be expected, it moved slowly eastward into the Atlantic (figs. 15 and 16). It continued its eastward track until February 24 when it was located nearly 900 miles east of Norfolk, Va., before turning northward. It then proceeded to make a large looping track and it was not until February 27 that it passed over Newfoundland on a steady northeasterly course (see track, fig. 16).

Although the High at the surface and aloft east of Newfoundland began to migrate slowly eastward after February 21 this movement did not signify the end of blocking action as was seen in the discussion of the 500-mb. level. Large, slow-moving Highs continued to characterize the circulation pattern for the remainder of the month and during much of March. The slow eastward progress of large-scale pressure systems can be illustrated by the fact that the ridge line over the Plains to the west of the Low on February 21 (fig 15) moved eastward during the following 5 days at an average speed of less than seven knots.

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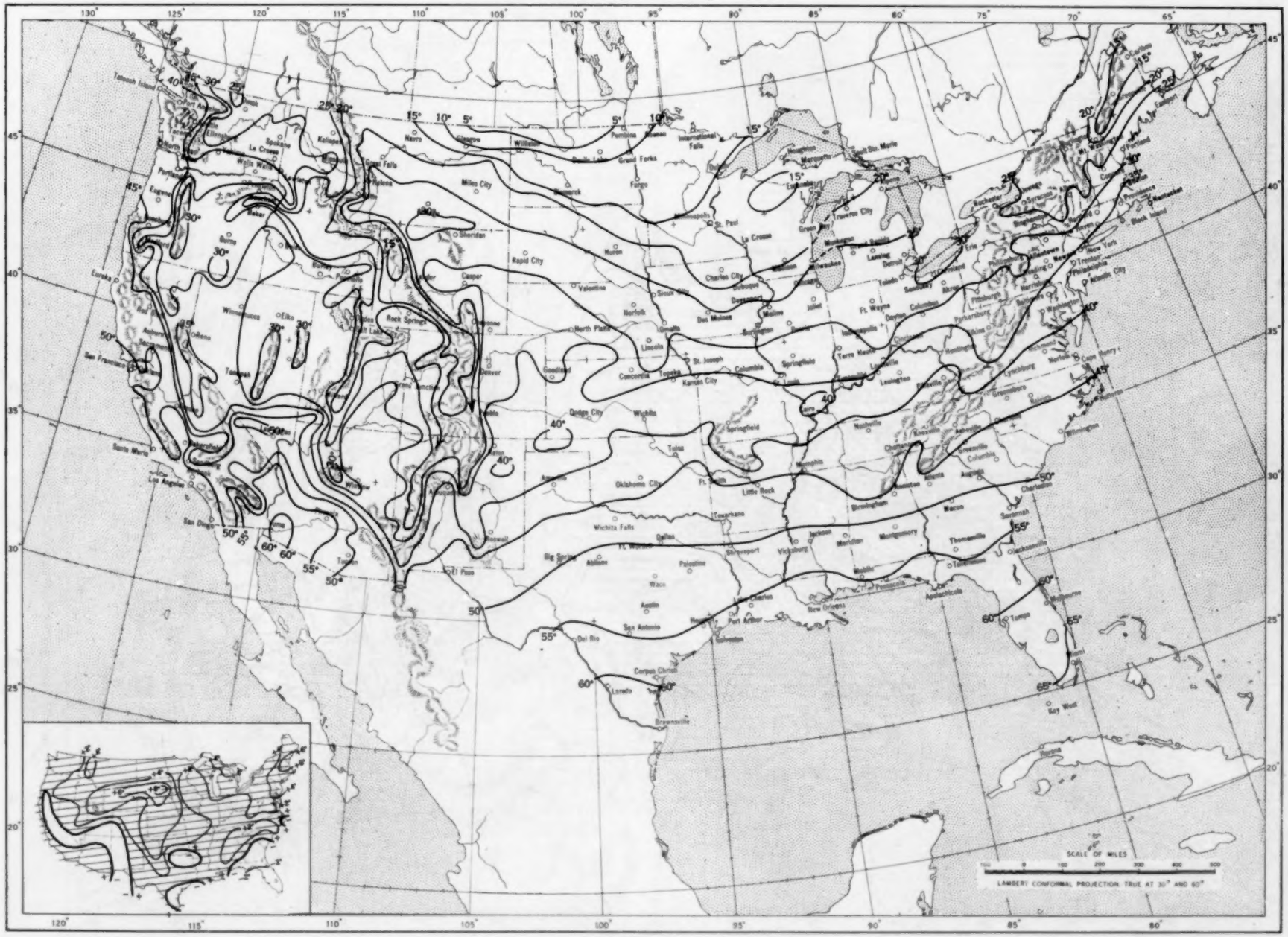
3. R. D. Elliott and T. B. Smith, "A Study of the Effects of Large Blocking Highs on the General Circulation in the Northern Hemisphere Westerlies," *Journal of Meteorology*, vol. 6, No. 2, April 1949, pp. 67–85.
4. R. Berggren, B. Bolin, and C.-G. Rossby, "An Aerological Study of Zonal Motion, Its Perturbations and Breakdown," *Tellus*, vol. 1, No. 2, May 1949, pp. 14–37.
5. C.-G. Rossby and H. C. Willett, "The Circulation of the Upper Troposphere and Lower Stratosphere," *Science*, vol. 108, No. 2815, December 10, 1948, pp. 643–652.
6. H. Riehl, T. C. Yeh, and N. E. La Seur, "A Study of Variations of the General Circulation," *Journal of Meteorology*, vol. 7, No. 3, June 1950, pp. 181–194.
7. E. H. Bowie and R. H. Weightman, "Types of Storms of the United States and their Average Movements," *Monthly Weather Review*, supplement No. 1, 1914.

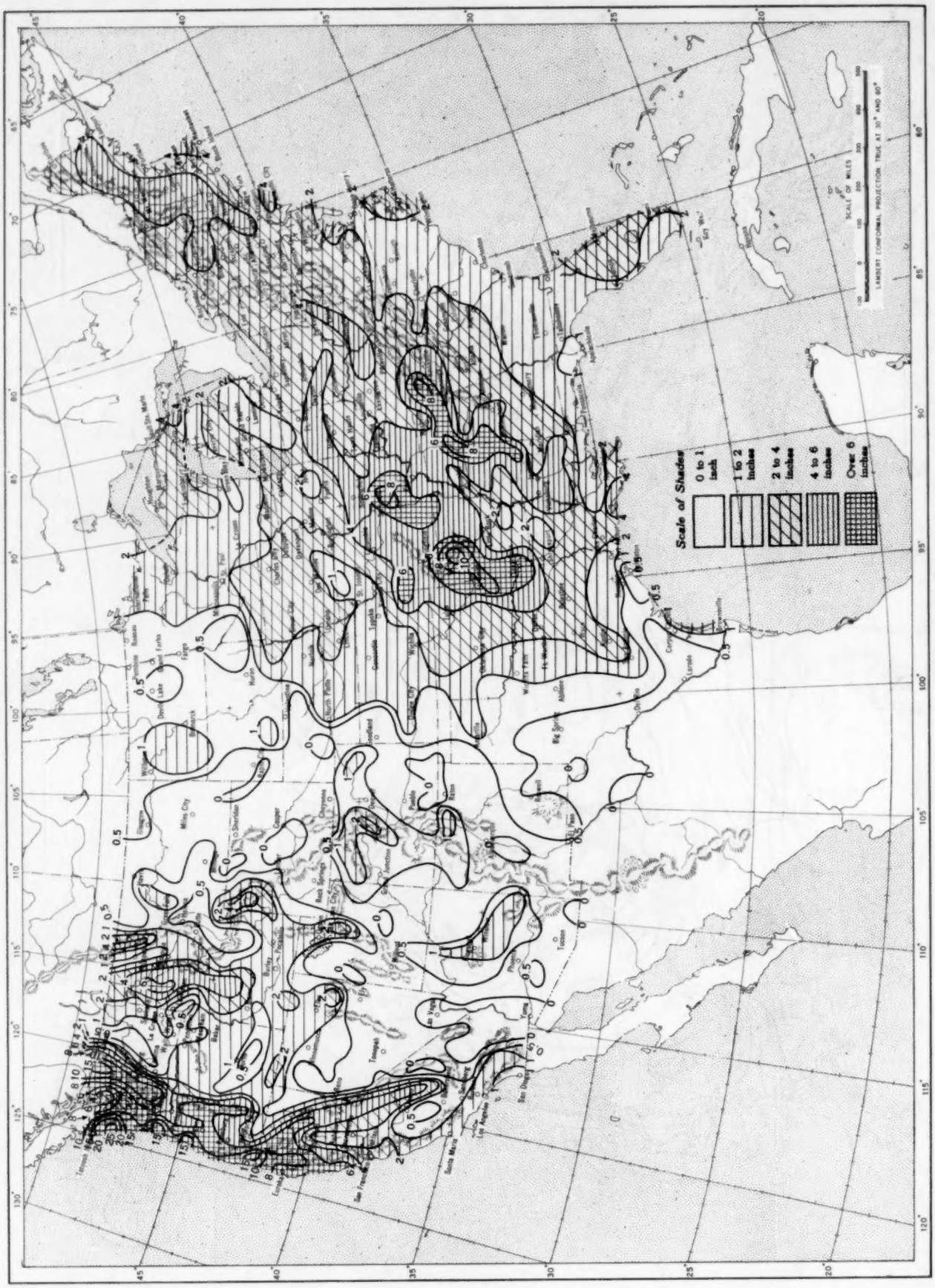
U. S. GOVERNMENT PRINTING OFFICE: 1951

Chart I. Average Temperature (°F.) at Surface, February 1951. Inset: Departure of Average Temperature from Normal (°F.), February 1951.



Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

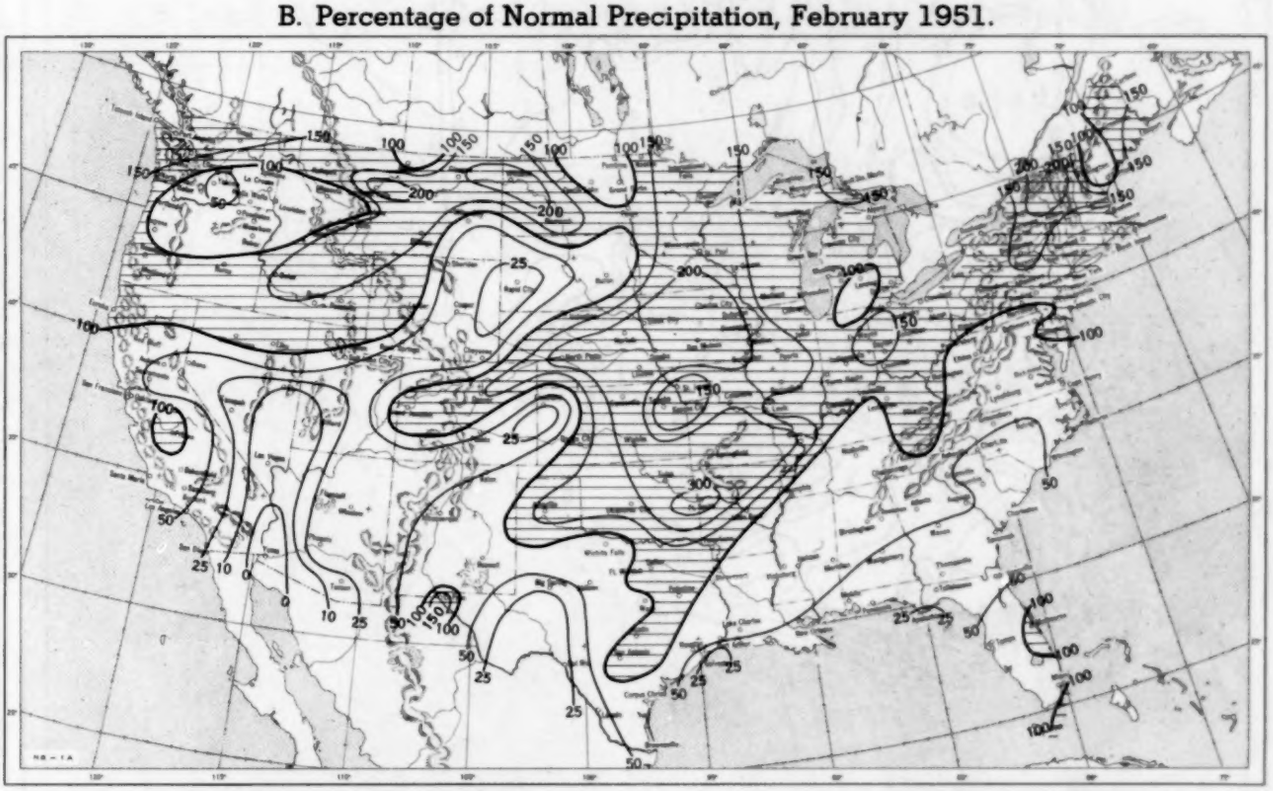
Chart II. Total Precipitation (Inches), February 1951.


Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°
SCALE OF MILES

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

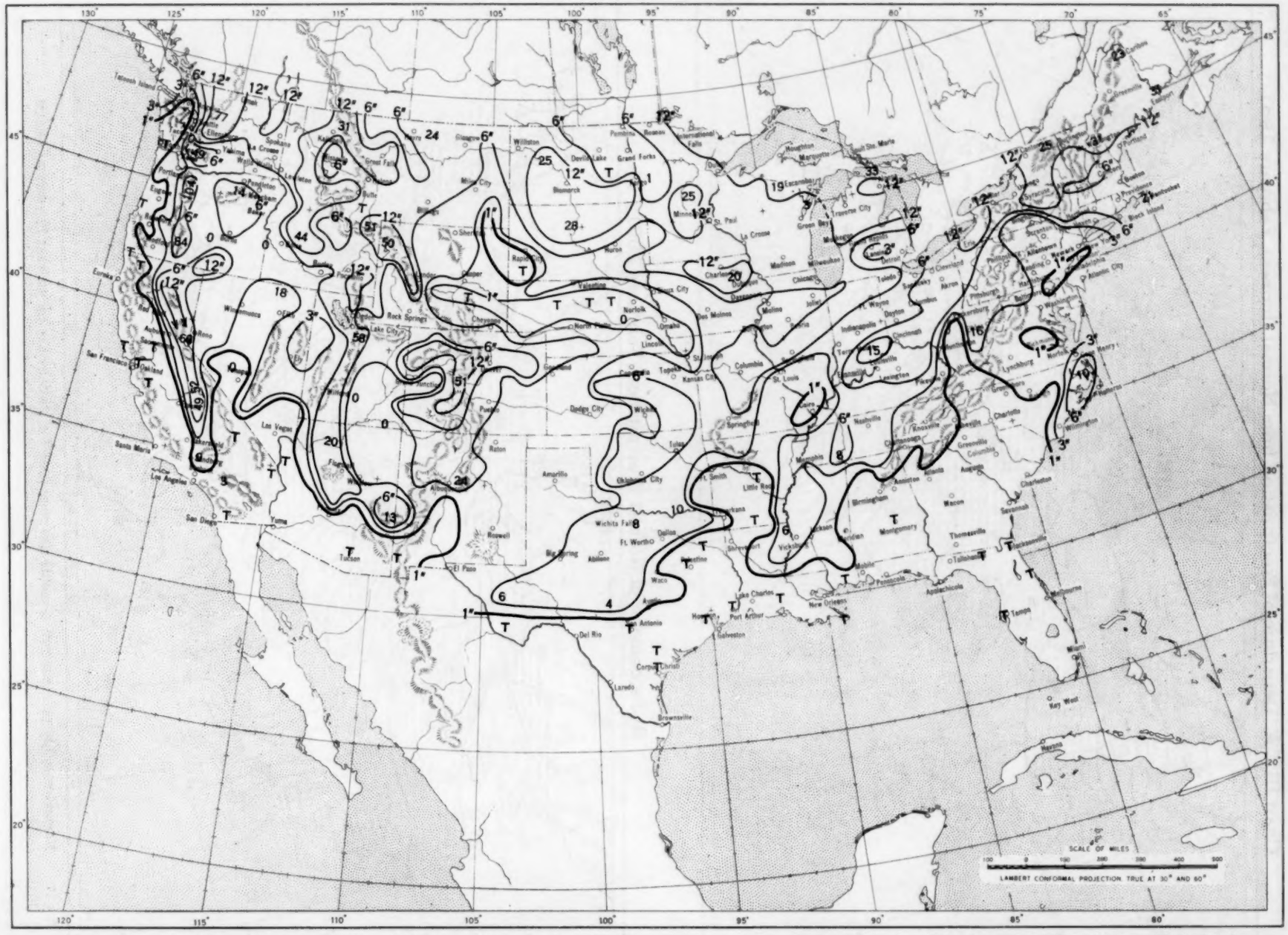
Chart III. A. Departure of Precipitation from Normal (Inches), February 1951.

B. Percentage of Normal Precipitation, February 1951.



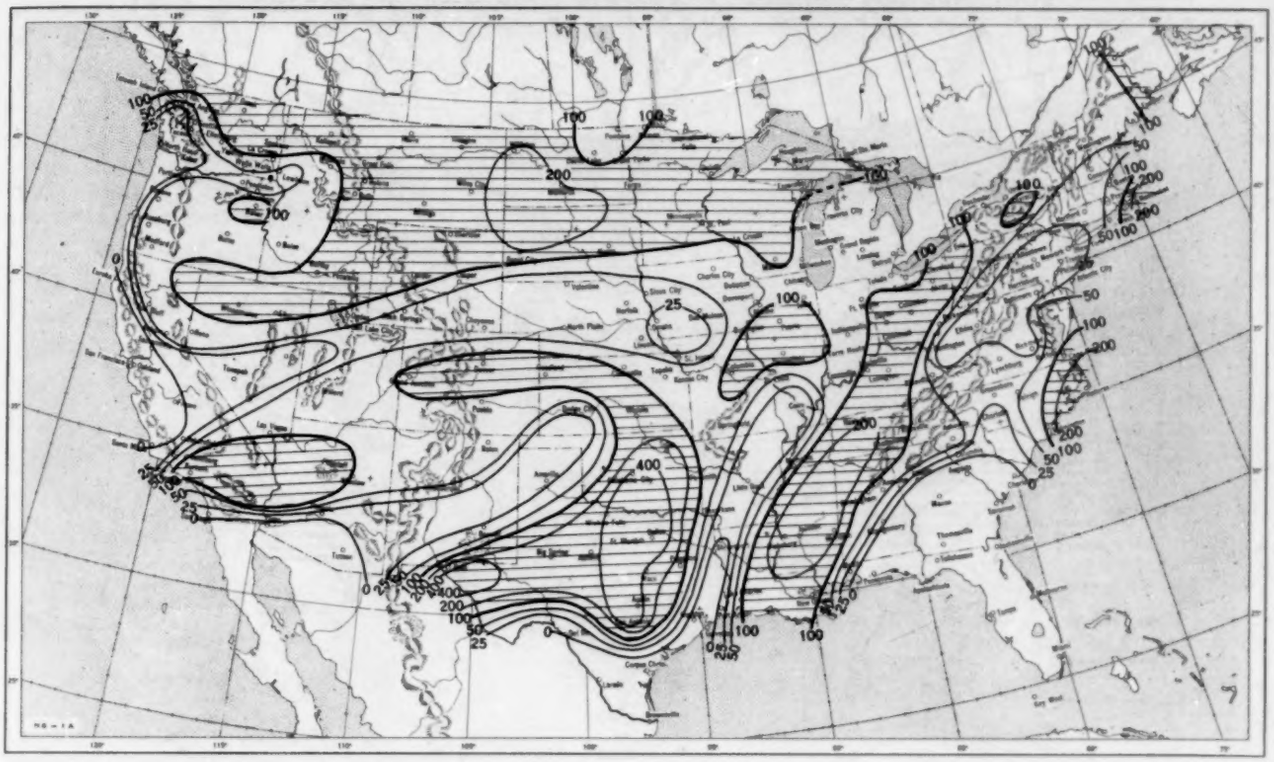
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), February 1951.

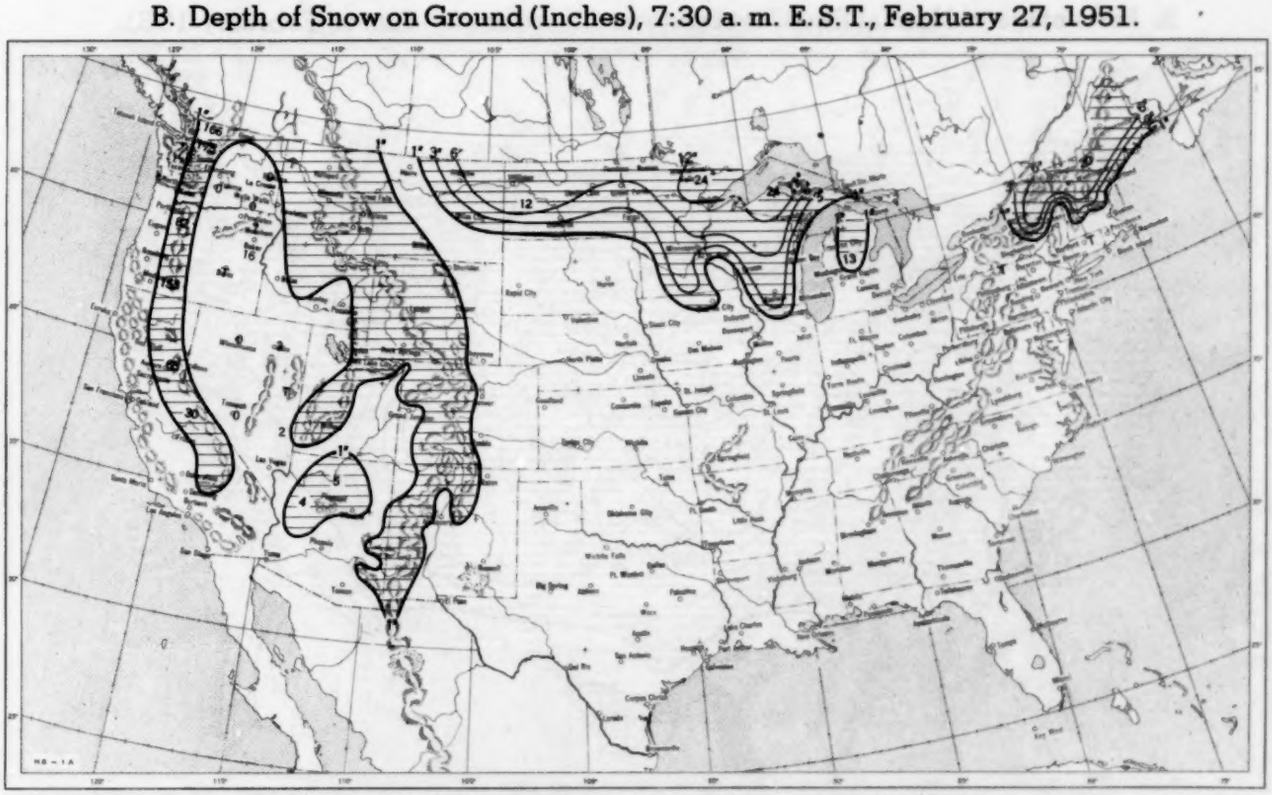


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, February 1951.

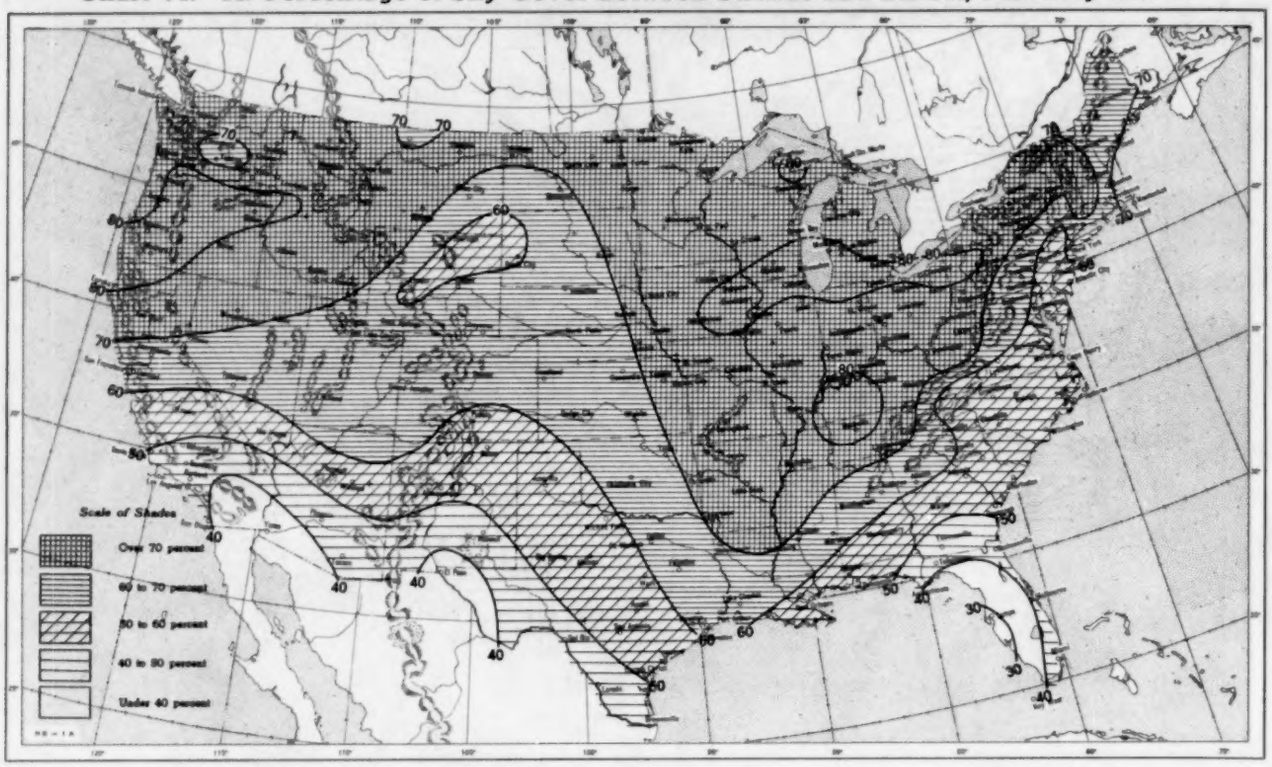


B. Depth of Snow on Ground (Inches), 7:30 a. m. E. S. T., February 27, 1951.

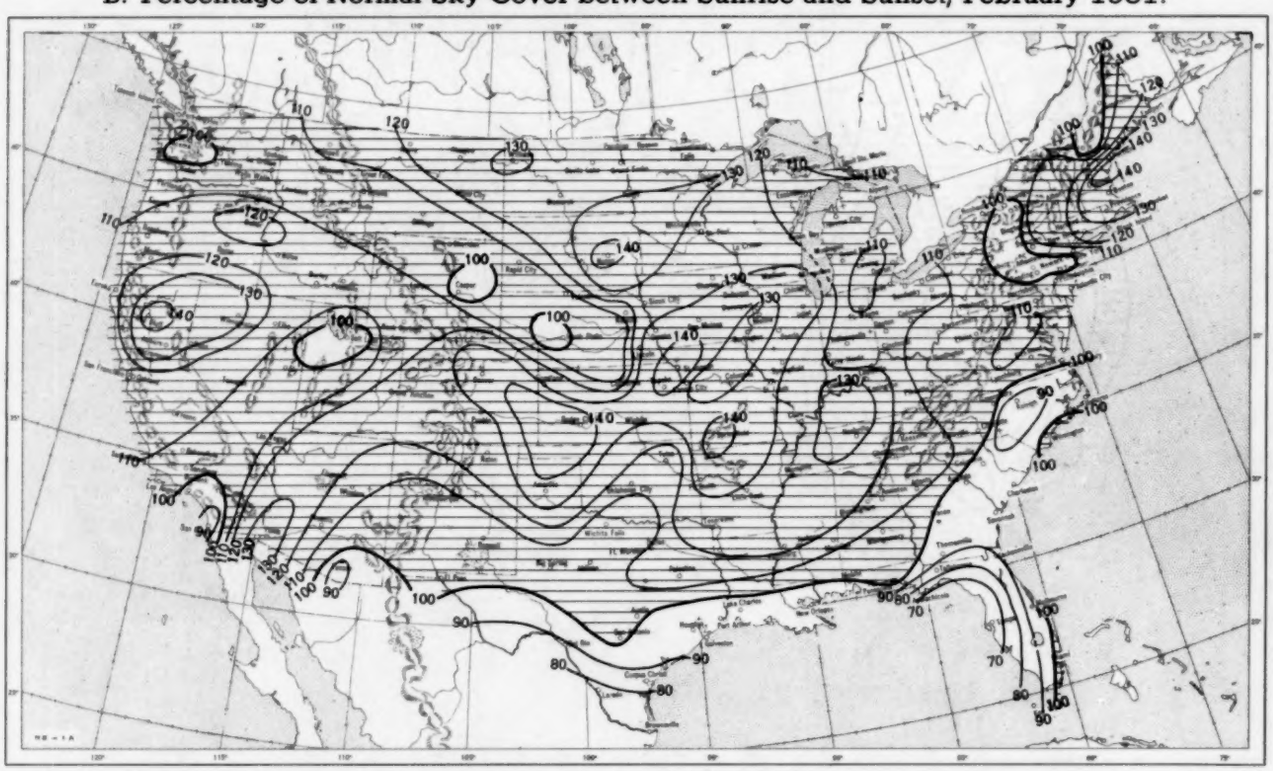


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, February 1951.

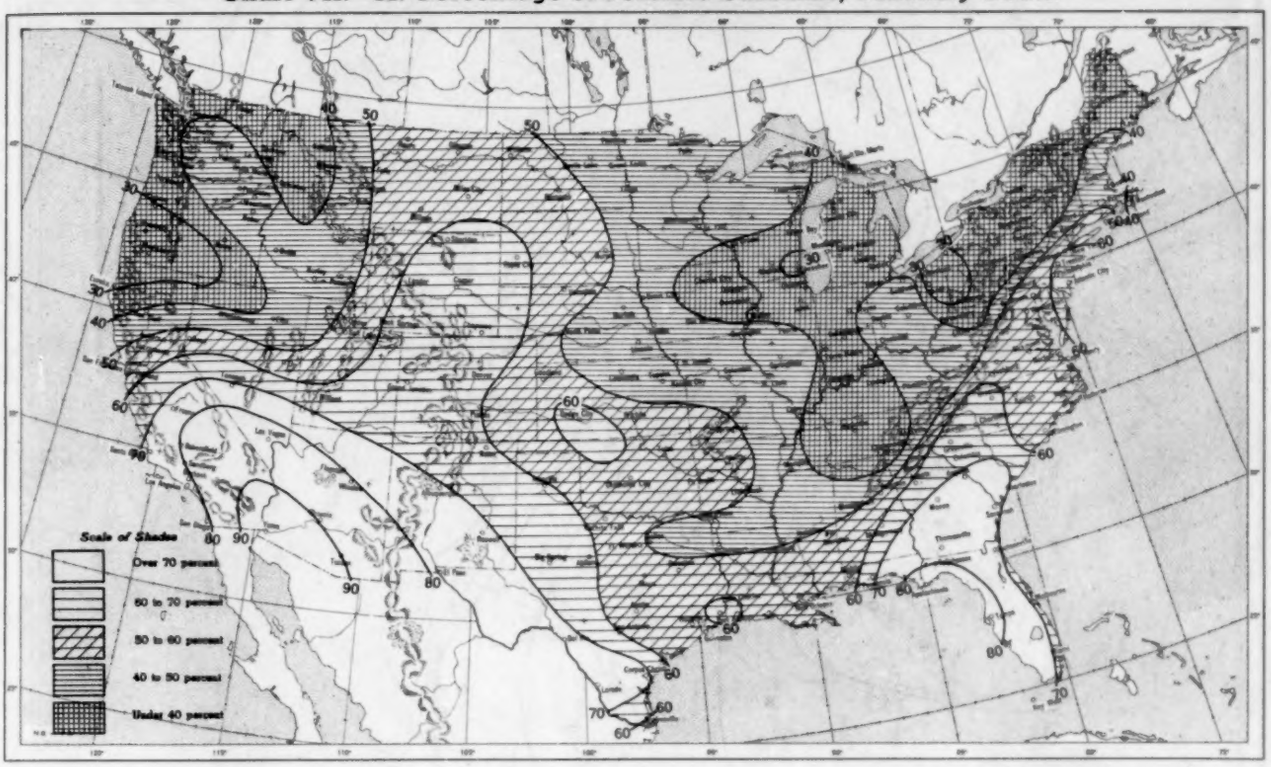


B. Percentage of Normal Sky Cover between Sunrise and Sunset, February 1951.

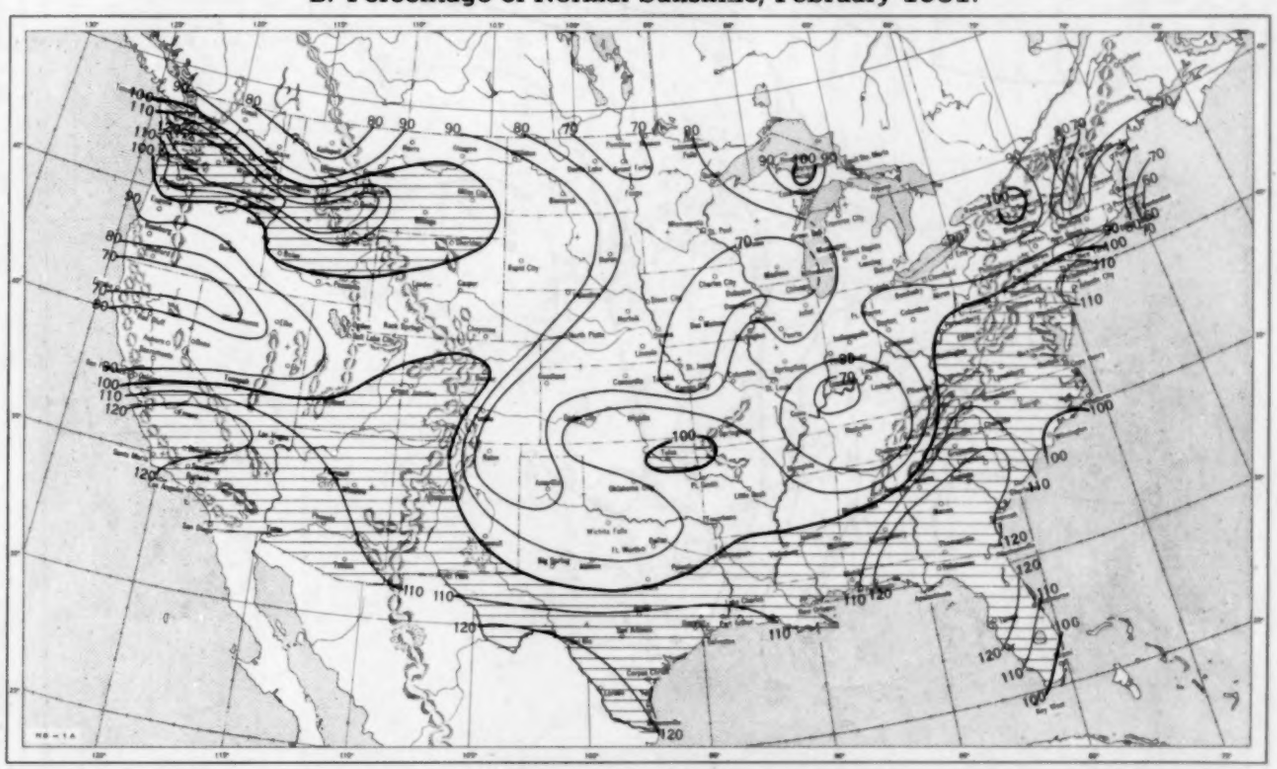


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, February 1951.



B. Percentage of Normal Sunshine, February 1951.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, February 1951. Inset: Percentage of Normal Average Daily Solar Radiation, February 1951.

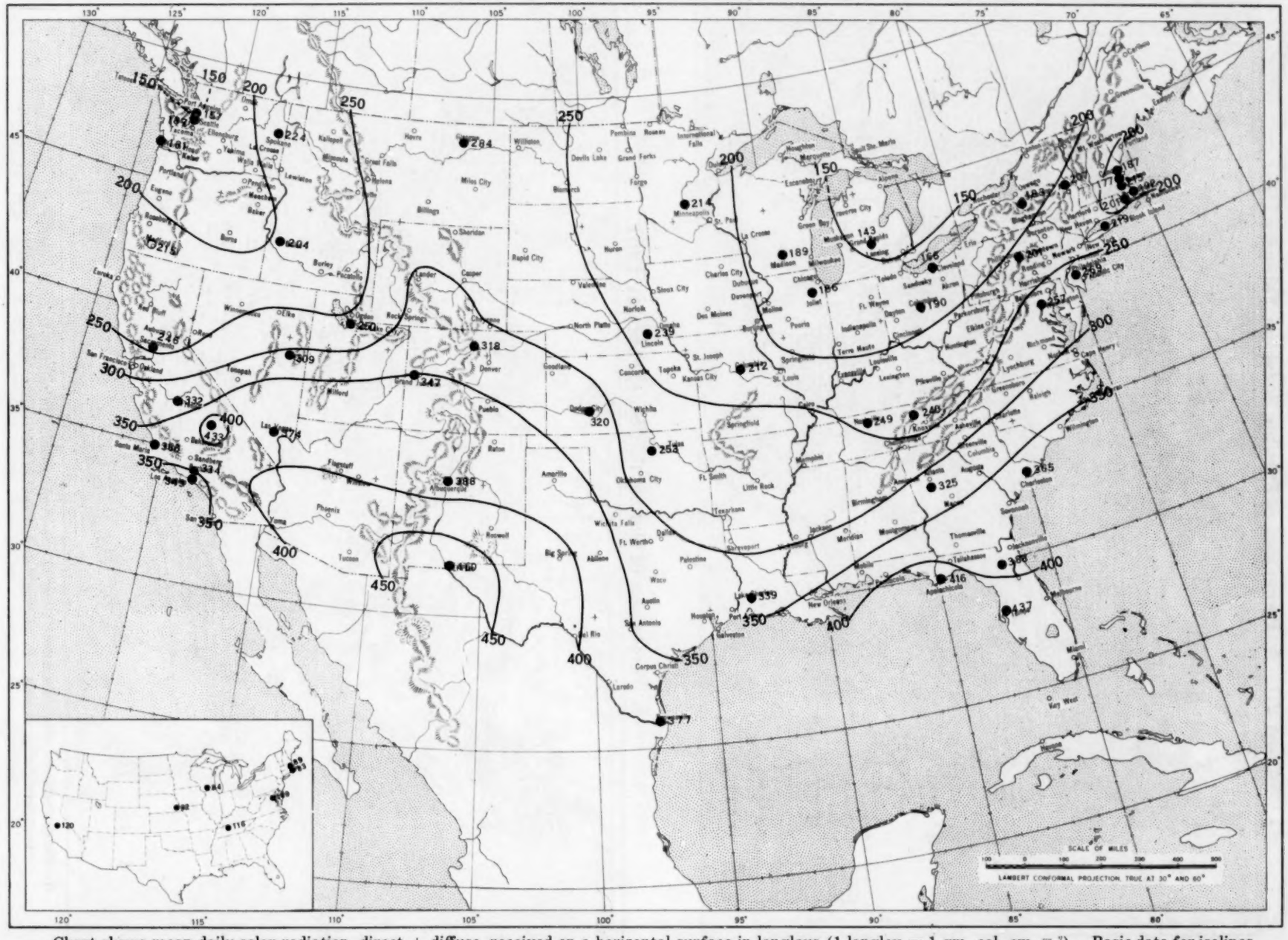
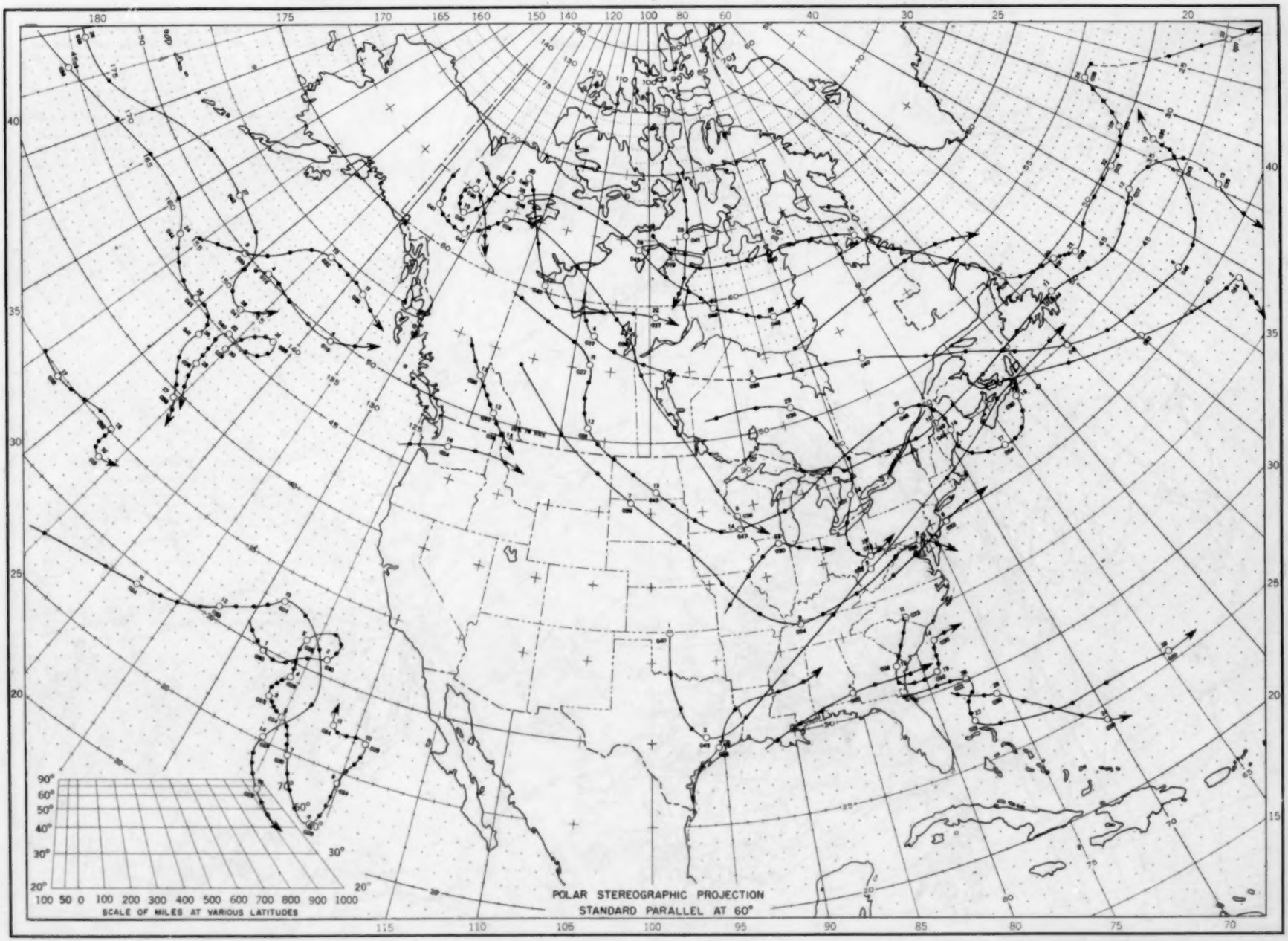


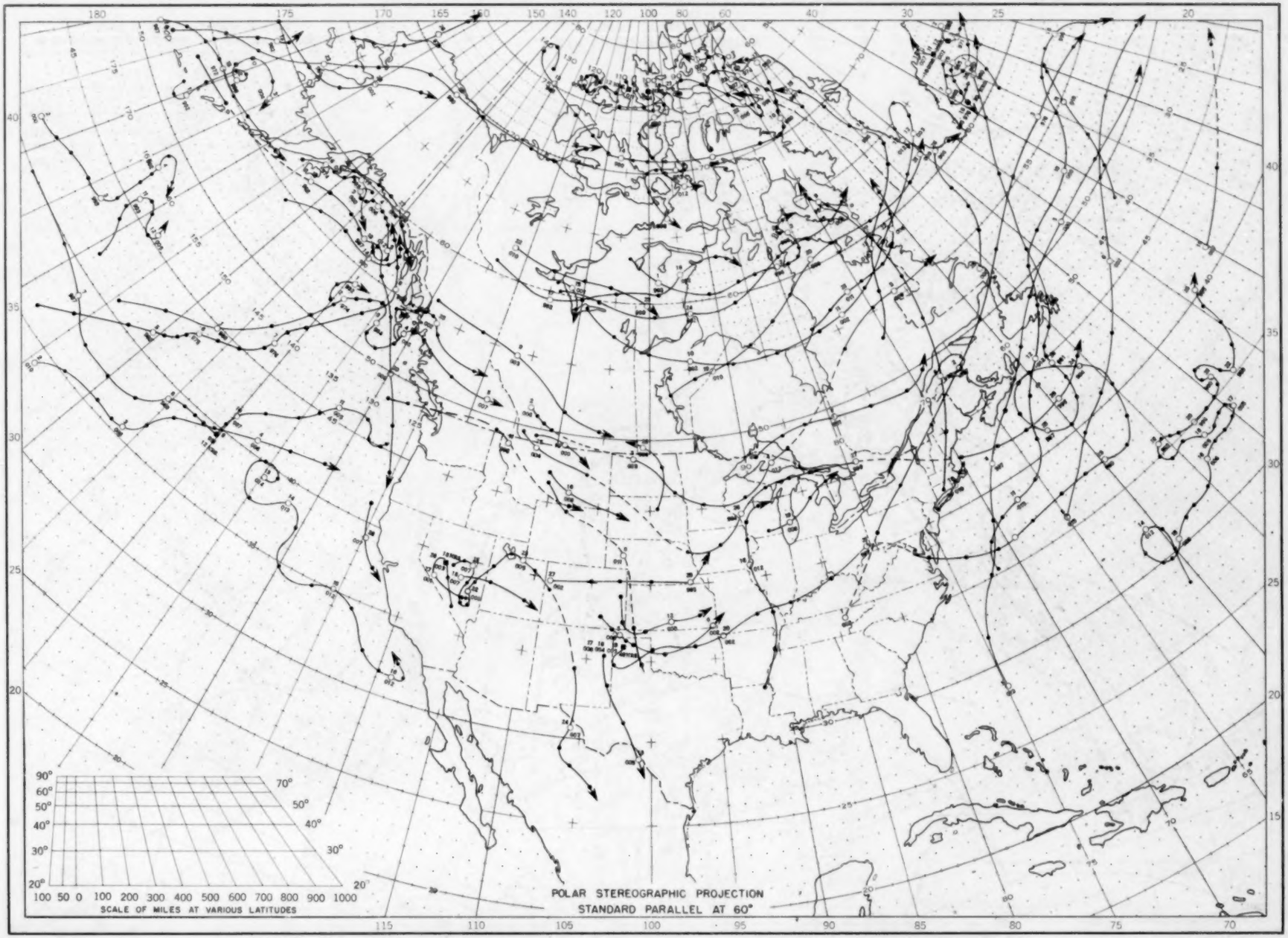
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, February 1951


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

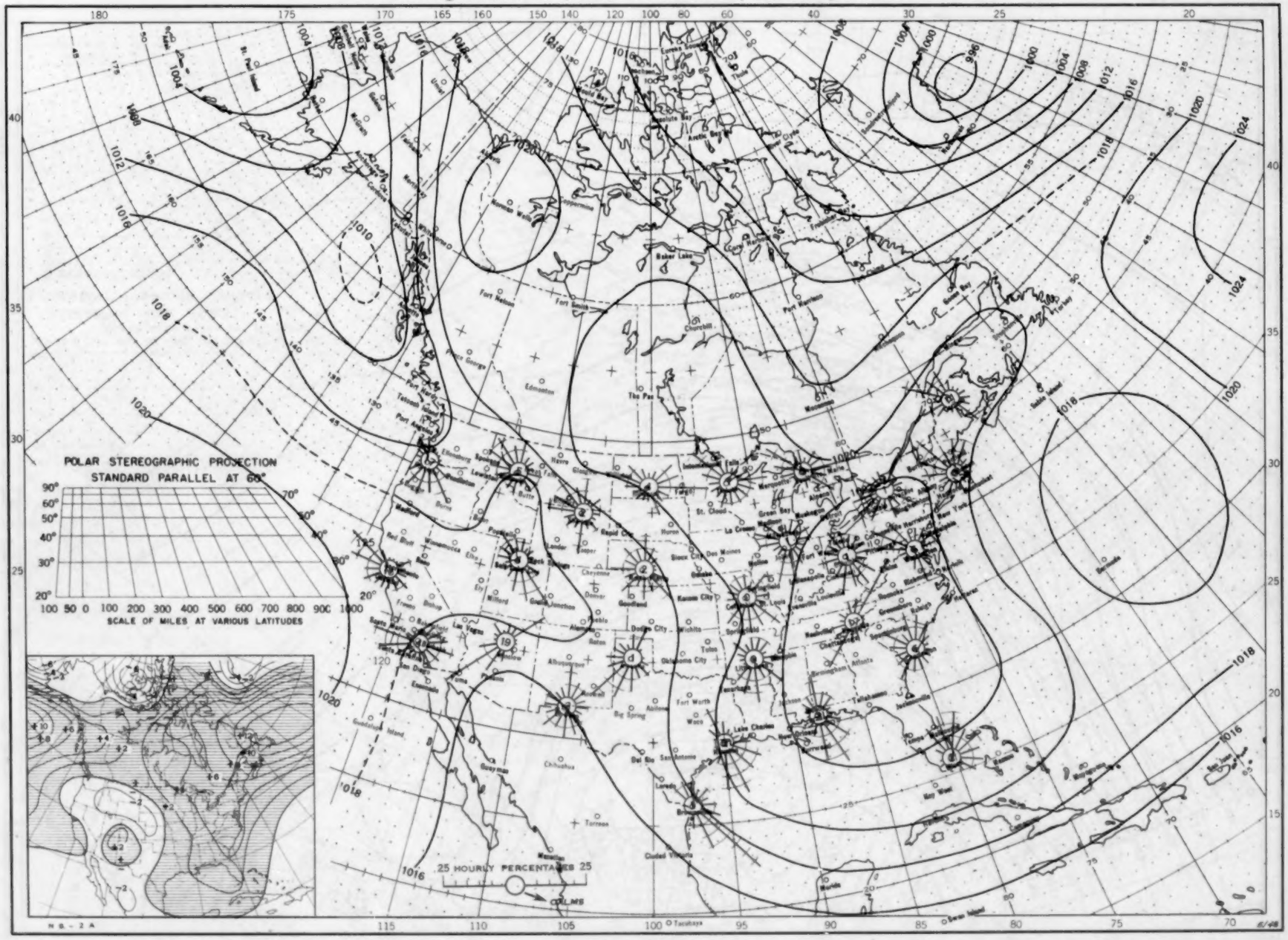
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, February, 1951.


POLAR STEREOGRAPHIC PROJECTION
STANDARD PARALLEL AT 60°
SCALE OF MILES AT VARIOUS LATITUDES
100 50 0 100 200 300 400 500 600 700 800 900 1000

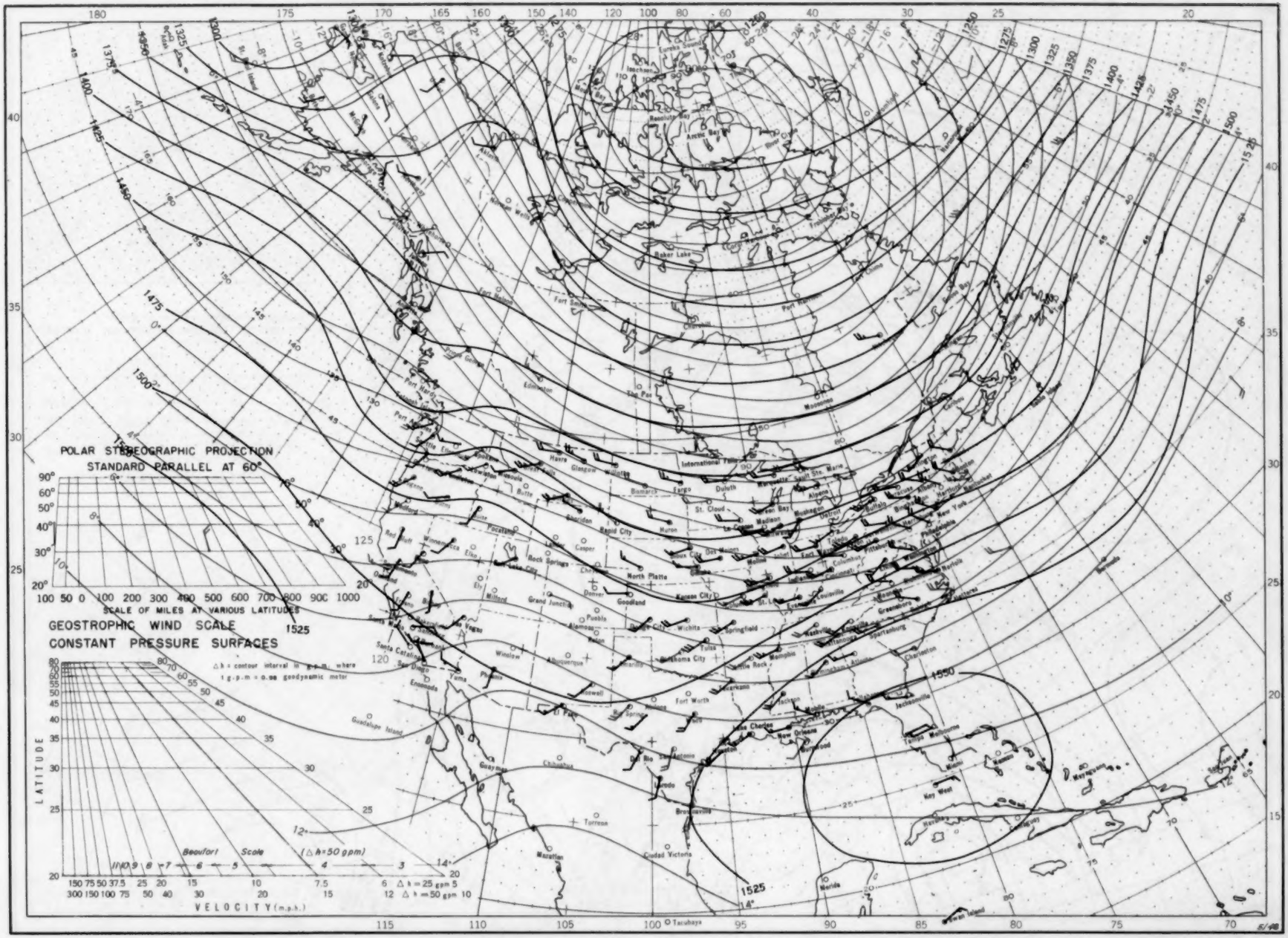
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, February 1951. Inset: Departure of Average Pressure (mb.) from Normal, February 1951.



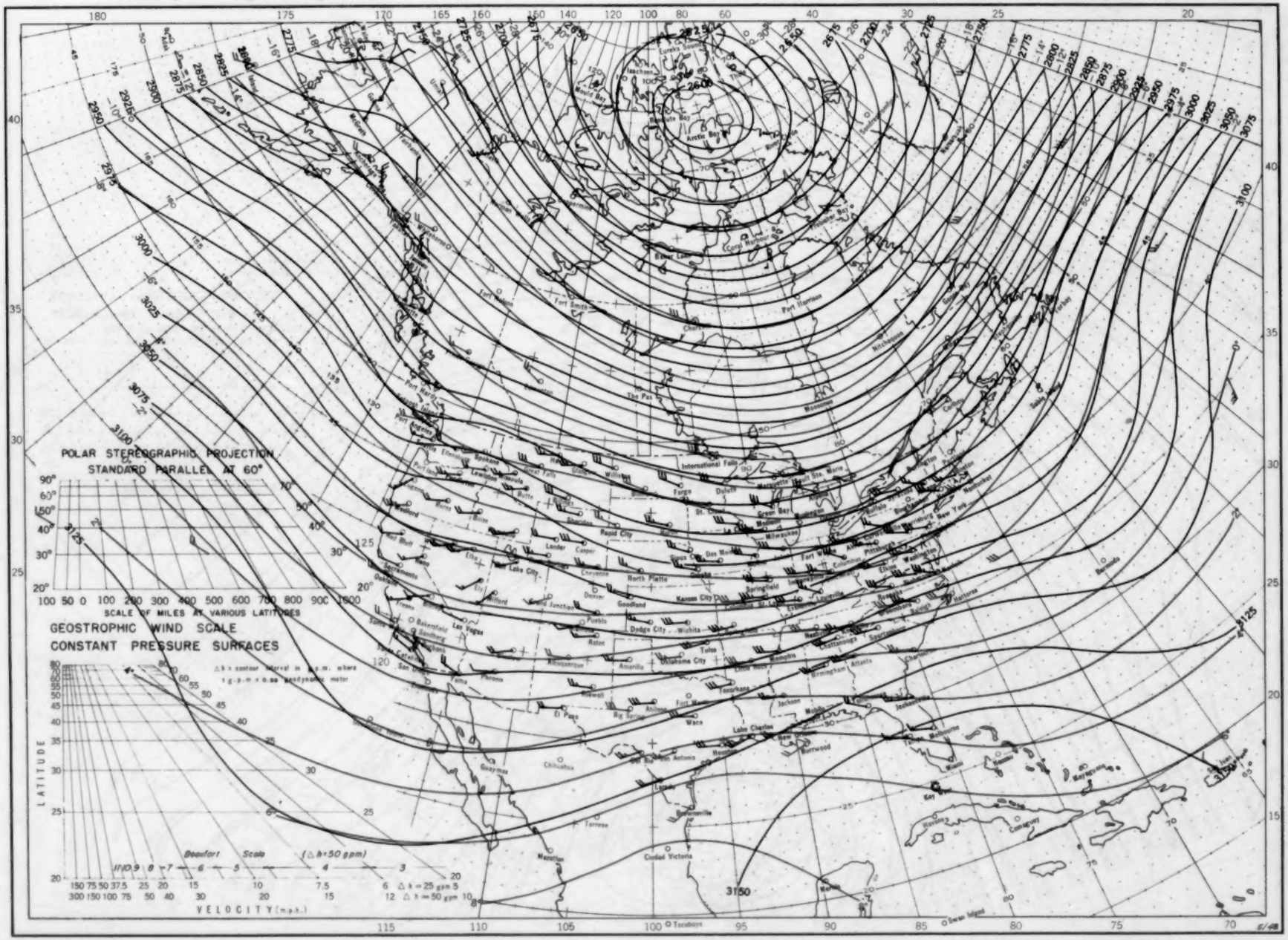
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid from map readings for 20 years of the Historical Weather Maps, 1899–1939.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), February 1951.



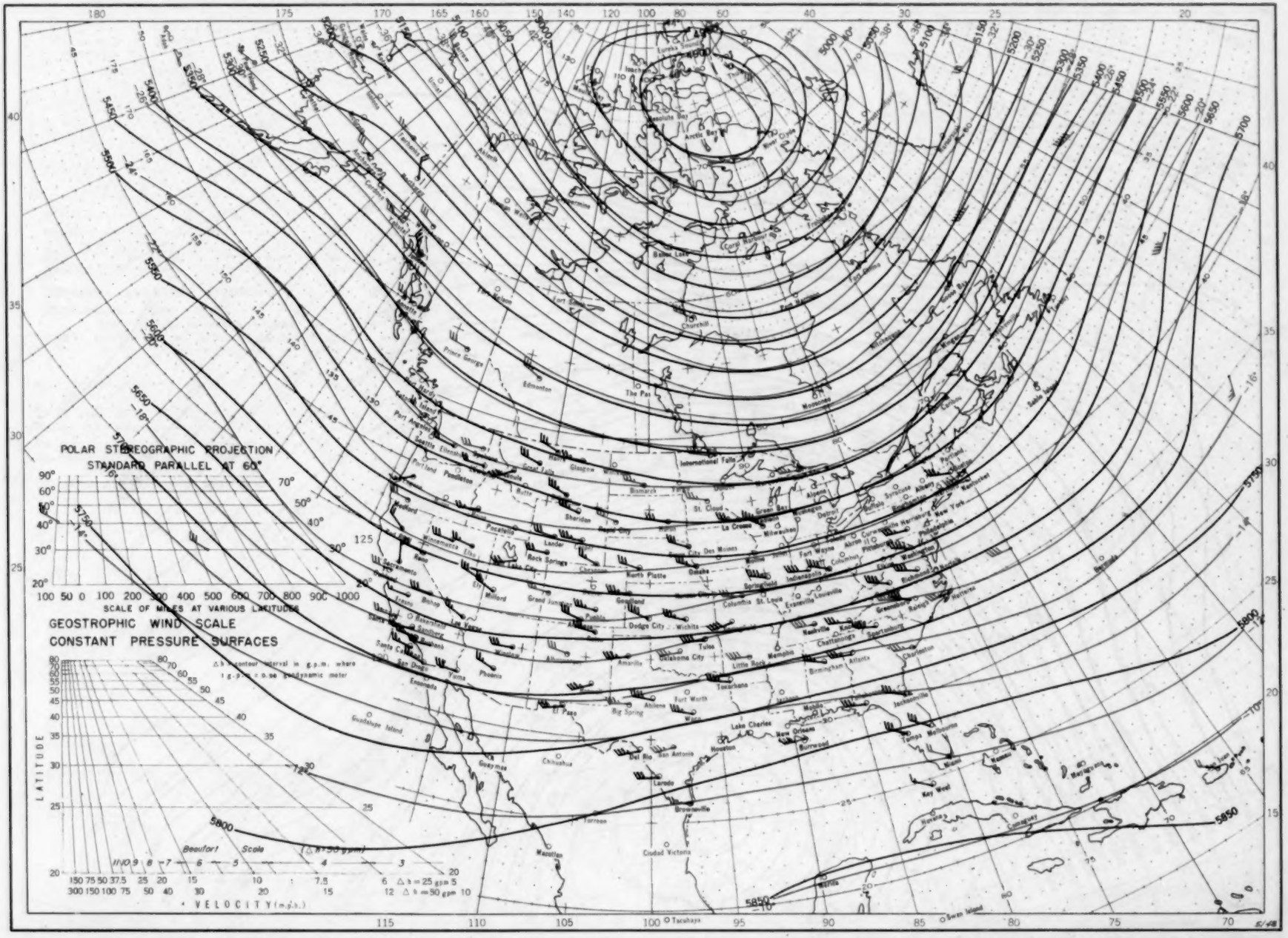
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), February 1951.



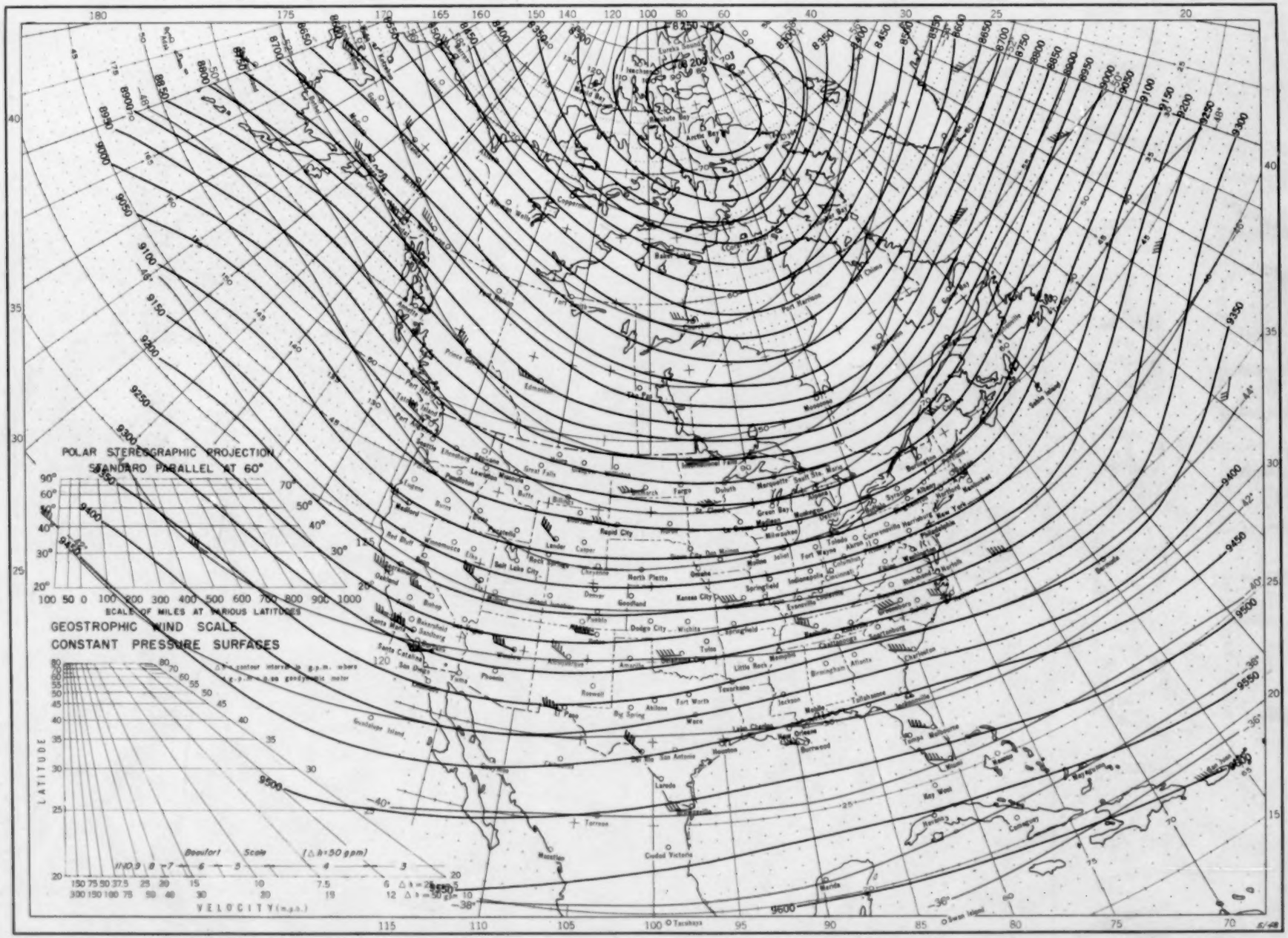
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), February 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), February 1951.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T.